Adaptive Learning Algorithms for Dynamic Control of Multilevel Converter

Synopsis of the Ph. D Thesis

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1 Abstract

Power converters are a technology that enables industrial processes driven by electric drive systems. They have the potential to be beneficial in a variety of applications, including as transportation (train traction, ship propulsion, and automotive applications), energy conversion, manufacturing, mining, and petrochemicals. But, now days, many of these applications requires high power to meet the requirement quality power to acquire higher production rates, cost reduction (on a large scale), and efficiency. Research and industry community in the field of power electronics has responded to this need in two ways: first, by improving semiconductor technology to provide greater nominal voltages and currents (now 8 kV and 6 kA) while preserving established converter typologies (in many cases, two-level voltage and current source converters) and developing novel multilevel converter typologies using traditional semiconductor technologies. The benefits of well-known circuit structures and control approaches were passed down in the first attempt. Although, semiconductors available today are more or little expensive, and when power levels increases, other power-quality standards must be met, requiring the use of power filters.

From the literature survey, it is found that few problems or limitations need to be addressed. Efficiency in multilevel converters need to be increased. Harmonics present in output voltage and current is the major cause of reduction in efficiency. Damping is required to be improved to stabilize load voltage or load current. The effect of load disturbance is not addressed completely with the multilevel converters.

In our research work, all the above limitations are studied in depth and tried to overcome all those limitations. In this thesis, the techniques to reduce total harmonic distortion in load voltage and load current, to increase efficiency, correction in power factor and problem of load disturbance is addressed and controlling techniques in open loop and closed loop are modified and limitations found with multilevel converters are resolved by large margin.

In our research work, initially we carried out our research work we simulated nine level multilevel converter with open loop without PWM. In open loop PWM method performance of multilevel converter is analyzed for R and RL load. We also simulated multilevel converter with open loop PWM technique. Here we used sine wave pulse width modulation technique for R and RL load. Due to the PWM, total harmonic distortion in load current and load voltage is reduced and efficiency is increased.

As we know that, with the open loop techniques, voltage or the current is not stabilized for the variation in load. Output voltage is obtained to the set reference value of 800 V peak. In our research work, we used three type of closed loop controllers namely proportional-integral-differential (PID), artificial neural network (ANN) and fuzzy logic controller (FLC). In the closed loop techniques, nine level multilevel converter is simulated for R, RL and motor load. All the closed loop techniques are also simulated for 200 V peak. Data samples obtained with PID controller are used for ANN and FLC type of controllers. Soft computing techniques used like ANN and FLC works in adaptive fashion. Adaptive nature of designed controllers is proved in our research work. In our research work we found that closed loop controllers.

Voltage feedback is used to adjust the output voltage. A proportional-integral-differential (PID) controller is typically used to adjust output voltage in order to reduce total harmonic distortion in load voltage and load current. To eliminate total harmonic distortion (THD), we replace the PID controller with an artificial neural network (ANN). Methods

based on the use of learning algorithms in closed loop are implemented, and total harmonic distortion is reduced to acceptable level.

In order to stabilize the output voltage, we additionally used a fuzzy logic controller in a closed loop circuit. It's also utilized to cut down on overall harmonic distortion in output voltage and current.

Adaptive learning algorithms by using Artificial Neural Network (ANN) and fuzzy logic controllers (FLC) are used to stabilize the output. It also reduced total harmonic distortion in output voltage and output current. We found that, variation in load for R and RL gives stabilized output. Closed loop controlling methods gives rise to lowest value of total harmonic distortion in load voltage and load current.

Performance in the form THD, power factor and efficiency are compared and presented in the thesis. Among used three closed loop controlling techniques, use of ANN offers best performance in the form of THD in load current and load voltage. Efficiency obtained is highest as compared other closed loop controlling techniques used in our research work. Use of ANN shows best result i.e. 2.96% THD in load voltage, 1.00% THD in load current and efficiency of 94% for RL load.

Results obtained with simulation are verified by hardware setup. All the open loop and closed loop controlling techniques are implemented by using Respberry Pi microcomputer system. In our research, open loop PWM is found to be best among open loop controlling techniques. In closed loop controlling techniques, ANN is found to be most effective as far as performance parameters are concerned.

2 Introduction

The use of high power has increased very widely in industrial applications. Nowadays, there is a requirement for quality power [1]. A multilevel converter consists of several levels of DC voltage as inputs and produces the required voltage. This multilevel converter technology is growing at a rapid rate. Multilevel converters are very widely used with non-conventional energy sources like wind and solar. PV cells are widely used as input sources to the multi-level converter.

The output of a multilevel converter consists of different steps of lower voltage. It has lower switching losses. The output consists of lower harmonic components. It can generate high power as required by the application. It generates high power quality [4]. Multilevel inverters can be used with high frequency and low frequency PWM. But high frequency PWM shows high frequency switching losses and lower efficiency, while low frequency PWM results in low losses and higher efficiency [5].

The use of multilevel converters is highly associated with windmills. It is widely used in pumps, conveyors, grids, and HVDC. These are the various topologies suggested for multilevel inverters, like cascaded multi-cell with different dc batteries, diode clamped, and capacitor clamped [6]. These various mechanisms suggest the method of generation of output voltage and current [7]. A cascaded H-bridge consists of different power converter units connected in series. With this type of connection, the voltage level and power level can be scaled easily. A diode-clamped inverter uses a group of series capacitors [8]. Flying capacitors use capacitors in floating conditions to clamp the voltage levels instead of series connected capacitors [9]. Cascaded H-bridge inverters neither use flying capacitors nor clamping diodes but isolation transformers to provide isolation among different input voltage sources.

There are various modulation methods and control mechanisms used for the purpose of control in multilevel converters. For example, pulse width modulation of sinusoidal type (SPWM), selective harmonic elimination using PWM (SHE-PWM), space vector modulation (SVM), and others. [10] [11]. Each unit power converter requires a different switching angle. To generate a switching angle, sinusoidal pulse width modulation is used with a high carrier frequency. Average output voltage should remain unaffected. Multilevel converters provide numerous benefits such as low input current ripples, lower filter capacitor and filter inductor values, lower output voltage THD, and a large gain in desired boost factor [12].multilevel converters are focused on applications such as medium and low voltage motor drives in industrial applications [13], interfaces in which renewable energy is the requirement of various systems [14], transmission systems in which flexible AC is used (FACTS), and traction drive systems [15], [16]. Improvement in the good power quality in the distribution network, shunt Active Filters used for voltage using PI, PID, and Fuzzy Logic Controller (FLC) for power line

conditioners (PLC) have been suggested [17]. A desired value of output voltage level to provide the power for a variation in loads with a minimum THD, a deadbeat-based proportional-integral (PI) controller with a battery cell as the main energy source for a stand-alone single-phase inverter with voltage source has been suggested [18].

There is a necessity for a control mechanism to control the DC input power. A novel technique is proposed. A mathematical model is proposed for multilevel converters [19]. There are control mechanisms suggested based on learning algorithms, which are evolutionary algorithms [20]. Particle swarm optimization is proposed [8]. Various conventional methods like space vectors are suggested [21]. An artificial neural network technique to calculate switching angles is explained [22].

There are various dynamics that occur in multilevel converters. A technique to overcome the fast dynamics is explained and suggested. Estimation of the reference vector is forwarded [23]. By taking into account mathematical equations of output voltage [24], selective harmonic elimination is suggested to calculate the switching angles. Real-time selective harmonic elimination is forwarded for the multilevel converter in which there are DC input sources with different magnitudes are used [25]. A model-based predictive model based on a state space model is suggested [26]. A novel natural frame control method is presented for single phase cascaded H-bridge multilevel converters [27]. A method of harmonic minimization is suggested in [28].

2.1 Multilevel converter basics

Multilevel converters are converters in which the output has multiple levels. Multilevel converters have wide application in AC traction and ship propulsion in which high switching rates would be required. Mainly, multilevel converters are available in three main typologies. Neutral point clamped, flying capacitor, and cascaded H-bridge are the typologies to be mentioned. The cascaded H-bridge has important advantages, like being easy to design. Sources of the same magnitude are to be applied to each bridge circuitry used in the multilevel converter. Sources of different magnitudes can be applied. When sources of different magnitudes are applied, it is called an asymmetrical configuration. Otherwise, it is called a symmetrical configuration. It consists of cascaded H-bridge circuits. A greater number of cascaded H-bridges gives rise to a greater number of levels in output voltage and output current. If there are more levels, there is a greater approximation to ideal sinusoidal output. Each bridge circuit uses a SPWM (Sine Wave Pulse Width Modulation) control strategy. A PWM (Pulse width modulation) signal is applied to the gate of each switch in the bridge circuit.The gating signals are generated with the technique known as SPWM. A sine wave is used as a modulating signal to generate PWM signals.

The use of the phase shift method to shift the phase of each cascaded H-bridge circuit proved fruitful. Switching angles are calculated and triggering pulses are applied to the gates of switches which are generated with the modulating signal and neural network. Fig. 2.1 shows the schematic diagram of a single-phase cascaded H-bridge nine-level inverter. Fig. 2.2 represents the load voltage waveform of a single-phase, nine-level multilevel inverter without the load. In this inverter, four identical units of cascaded h-bridge are used. All four converter units are connected in series.

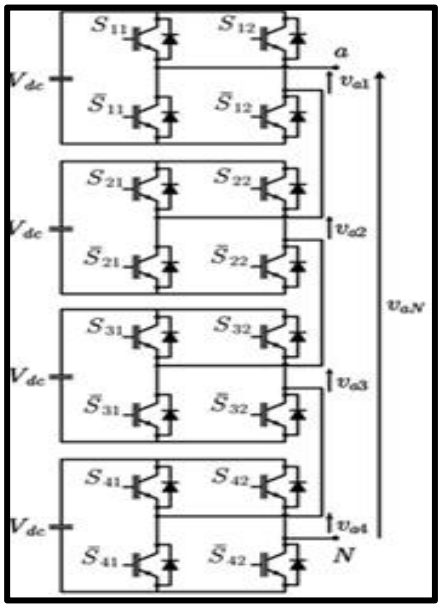

Fig.2.1 Connection schematic of a single phase cascaded H- bridge Nine level Inverter

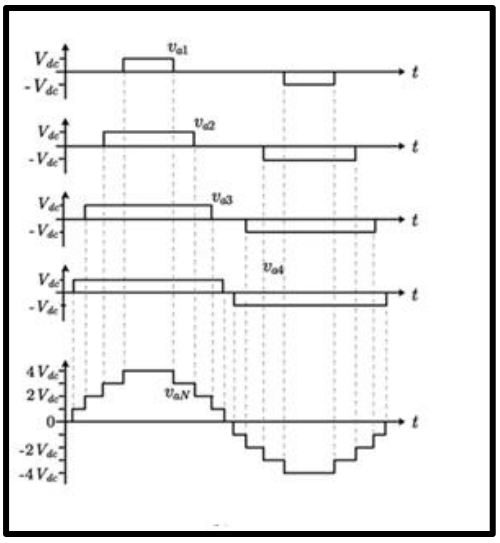

Fig. 2.2 Load voltage waveform of a cascaded nine level Inverter

Each bridge circuit is responsible for producing one level of positive magnitude in the positive half cycle and one level of negative magnitude in the negative half cycle in the output voltage waveform. A voltage of the same magnitude is applied to each cascaded H-bridge. In the upper bridge circuit, to obtain a positive half cycle of output voltage, two switches, namely *(S11,* $\bar{S}12$ *)* are gated, and therefore, these two switches

are turned on. Switches, namely (S12, $\bar{S}$11) are not provided with gating pulses, and therefore, these two switches remain in an off state. To obtain a negative half cycle of output voltage (S11, $\bar{S}$12) are not gated so that these two switches remain in an off state. The other two switches (S12, $\bar{S}$11)) are triggered so that these two switches go into the on-state and vice versa. This cascaded H-bridge inverter produces nine levels in the output voltage waveform. The peak of the output voltage is n times V_{dc} in the positive half cycle and the same voltage level in the negative half cycle. Therefore, in a nine-level inverter, four voltage levels are in the positive half cycle and four voltage levels are in the negative half cycle. In positive half-cycle output voltage levels, V_{dc}, $2V_{dc}$, $3V_{dc}$, and $4V_{dc}$. In the negative half cycle, output increases from zero to $-4V_{dc}$ and again back to zero in the step of V_{dc}.

Each unit is responsible to generate one voltage level in positive half cycle and one voltage level in negative half cycle. Therefore we can see that, total number of voltage levels in positive half cycle and number of levels in negative half cycle including zero voltage level are given by the following equation

$$m = 2n+1 \text{----------} \quad (1)$$

Where m indicates total number of levels and n indicates number of cascaded H-bridge circuits.

2.2 Feedback control in Multilevel inverter

Voltage feedback is needed to be employed in order to maintain a constant output voltage. With the changes in load, output voltage is varied without the use of a controller. To obtain a constant output voltage, generally a P-I controller is used. In our research work, the P-I controller is replaced with an artificial neural network to overcome the limitations encountered with the use of the P-I controller. A neural network is used as a controller to minimise the error between the output voltage and the reference voltage. Data samples required to train the neural network are obtained by the simulation of a multilevel converter in which a P-I controller is used. The use of neural networks as controllers has proven to be beneficial and dependable in the power electronics and drive areas to reduce error and control output voltage. It is used to control the output voltage applied to the load. Harmonic elimination in PWM inverters is achieved with help of a neural network controller and Fuzzy logic controller.

3 Research objectives

After a comprehensive literature survey of controlling methods, we identified the following research gaps:

3.1 Research Deficits

1. Total harmonic distortion is the major cause of reduction in efficiency.
2. Harmonics in output results in more source current and it causes reduction in efficiency.
3. Voltage balancing problem in input voltage sources is the main problem.
4. Damping need to be improved to stabilize the output.
5. Problem of load disturbance is not addressed completely.
6. Stability achievement is a major issue.

3.2 Goals of Research

The main objective is to propose a novel technique of controlling output voltage and output current in multilevel converters that reduces total harmonic distortion in output voltage and output current and increases the efficiency.

Based on the above lacunae and observations, we set the following research objectives:

1. To simulate and compare the results in the form of THD, power factor and efficiency in open loop control methods using nine- level cascaded H-Bridge converter for R and RL (non-linear) loads.
2. To simulate and compare the results in the form of THD, power factor and efficiency in closed loop(PID, Fuzzy logic and Artificial neural network) control methods using nine- level cascaded H-Bridge converter for R and RL (non-linear) loads.
3. To implement open loop and closed loop methods by hardware and compare the performance in the form of different parameters .

4 Literature Review

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using PI, PID, and Fuzzy Logic Controller (FLC) for power line conditioners (PLC) have been suggested [17]. A desired value of output voltage level to provide the power for a variation in loads with a minimum THD, a deadbeat-based proportional-integral (PI) controller with a battery cell as the main energy source for a stand-alone single-phase inverter with voltage source has been suggested [18].There is a necessity for a control mechanism to control the DC input power. A novel technique is proposed. A mathematical model is proposed for multilevel converters [19]. There are control mechanisms suggested based on learning algorithms, which are evolutionary algorithms [20]. Particle swarm optimization is proposed [21]. Various conventional methods like space vectors are suggested [22]. An artificial neural network technique to calculate switching angles is explained [23].

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5 Contribution

From the literature, it is found that there are various control methods available to control the output voltage and output current in a multilevel converter. As we discussed, the output voltage of a multilevel converter needs to be stabilized. Open loop, open loop PWM, closed loop PWM using PID and fuzzy logic controller methods are simulated with MATLAB. Results obtained with ANN techniques are compared with the results obtained with fuzzy logic controller algorithm. Results obtained by simulation are verified by hardware implementation. Open loop, open loop PWM, ANN based closed PWM and Fuzzy logic controller based closed loop techniques are implemented with hardware and the results are compared with the results obtained by simulation.

5.1 Contribution-1: Simulation and comparison of open loop controlling methods for R and RL loads

Open loop control technique is used very widely. Open loop control techniques are implemented without and with PWM. Results with PWM gives less value of THD and high efficiency. In combination with open loop, various evolutionary algorithms and ANN is also used. Comparison of above two techniques in the form of performance parameters is done and results are tabulated. Different types of loads, R and RL are tested for simulation and their performance is compared. Different loads with different values, different power factor and wattage are used.

1. Open loop control technique
2. Open loop PWM control technique

5.1.1 Open loop control technique

With the open loop control technique, nine level multilevel is implemented with the help of MATLAB. Four cascaded H-bridge circuits are implemented. MOSFETS are used as switches. Each bridge circuitry is on for a specific duration in each half cycle. Generally, each bridge circuitry is on for $180^0/k$, where k is the number of cascaded H-bridges in a multilevel converter. Each bridge circuitry is powered by a single dc supply. In our case, we applied a constant DC supply of 50 V to each bridge circuit. Pulse generators are used to apply the gate pulses to the switches used in the multilevel converter. Pulses are applied to the switches and are phase shifted in comparison with

pulses applied to the adjacent cascaded H-bridge circuit. Fig. 5.1 to fig. 5.5 represents the simulink diagram, output voltage, FFT analysis of output voltage, output current and FFT analysis of output current, respectively. The open loop technique results in a high value of THD.

Table 5.1 Circuit parameters for simulation

Sr. No.	**Parameters**	**Values**
1	No. of Converters	4
2	No. Of Levels	9
3	DC input Voltage	200 V
4	Load Resistance	100 Ω
5	Load Inductance	140 mH
6	Filter Capacitor	100 μF
7	Filter Inductor	30 mH

Motor load specifications are as given below in table 5.2

Table 5.2 Motor load specifications

Sr. No.	**Parameters**	**Values**
1	Voltage	550V
2	Frequency	50Hz
3	Main winding stator resistance	2.02 ohm
4	Main winding stator inductance	7.4e-3
5	Main winding mutual inductance	0.1772H
6	Auxillary winding stator resistance	7.14 ohm
7	Auxiliary winding stator inductance	8.5e-3H
8	Nominal power	0.25*746 W

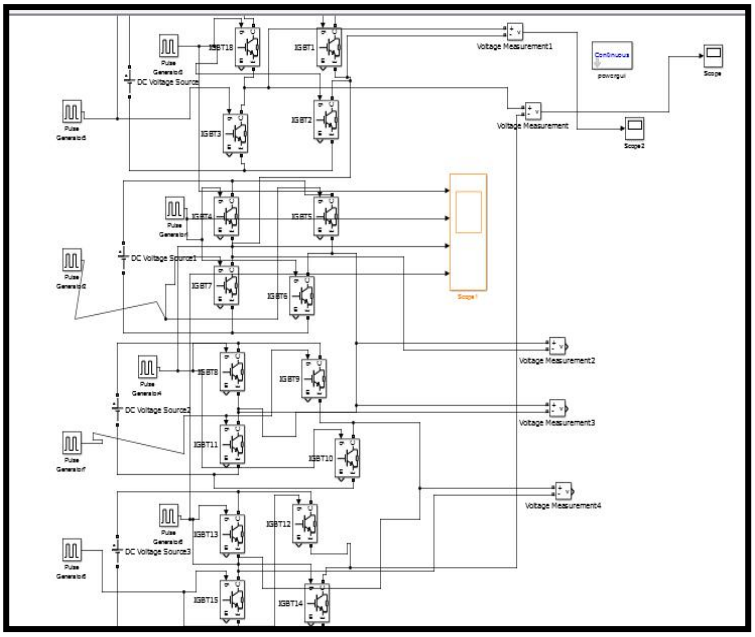


Fig. 5.1 Simulation diagram of open loop control technique

The output voltage is given by,

$$v(wt) = \sum_{n=1,3,5}^{\infty} \frac{4Vdc}{n\pi}(\cos(n\Theta_1 + \text{----------} + \cos(n\Theta_s))\sin(nwt) \text{ ----------(1)}$$

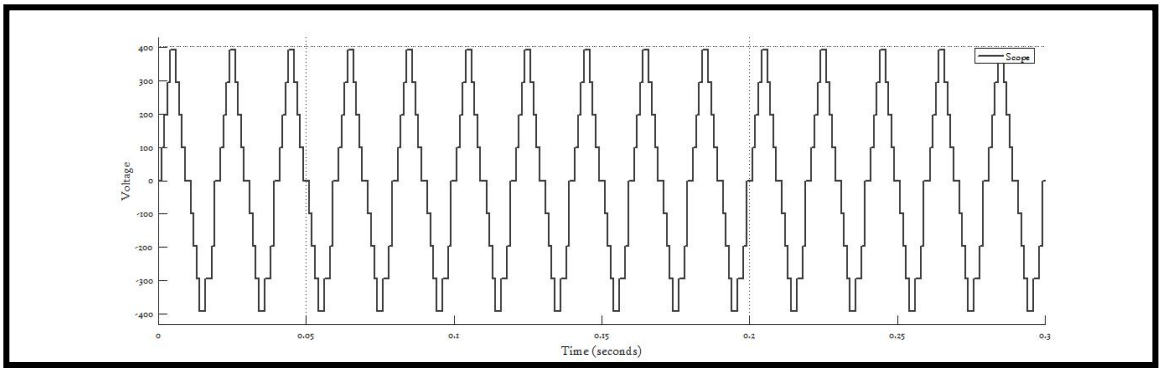


Fig. 5.2 Simulated output voltage waveform for R load

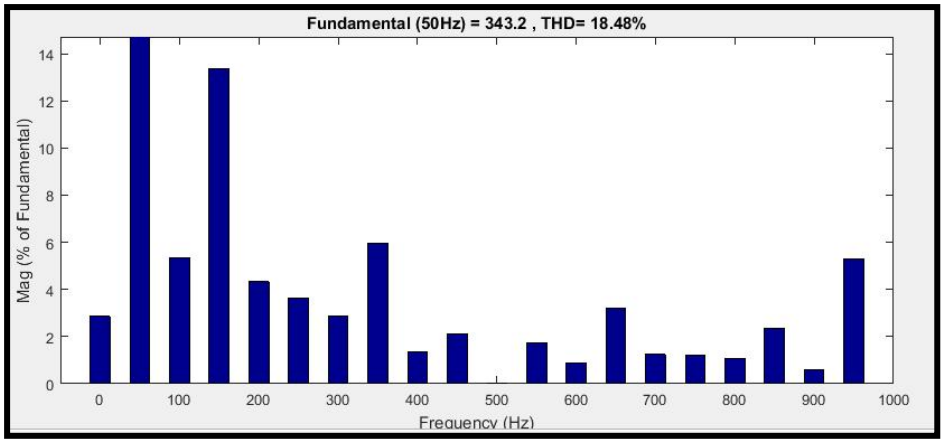


Fig. 5.3 FFT Analysis for simulated output voltage waveform for R load

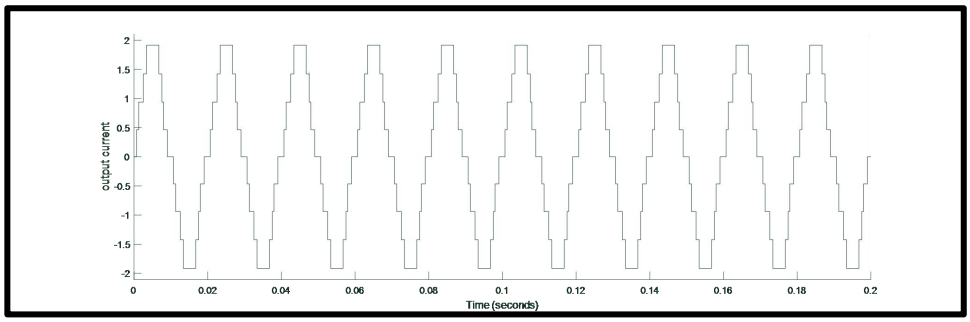


Fig. 5.4 Simulated output current waveform for R load

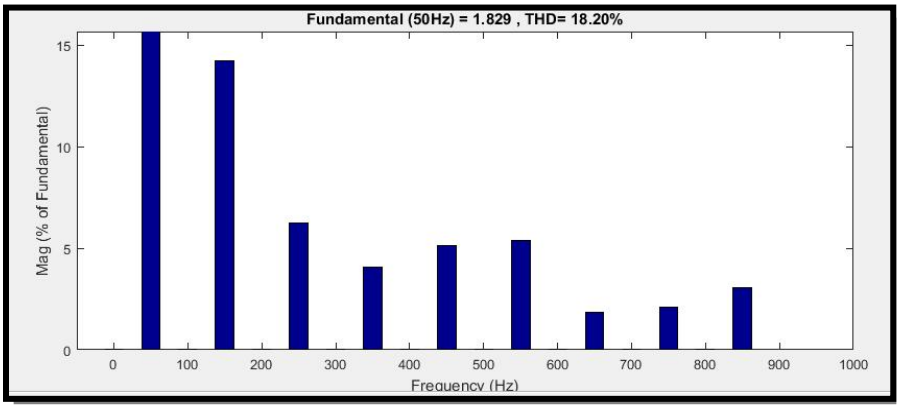


Fig. 5.5 FFT Analysis for simulated output current waveform for R load

Table 5.3 Parameter values in open loop technique for R load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	18.48%	18.20%	134.37V	1.41A	171.05W	190.05 VA	0.9	84%

Voltage

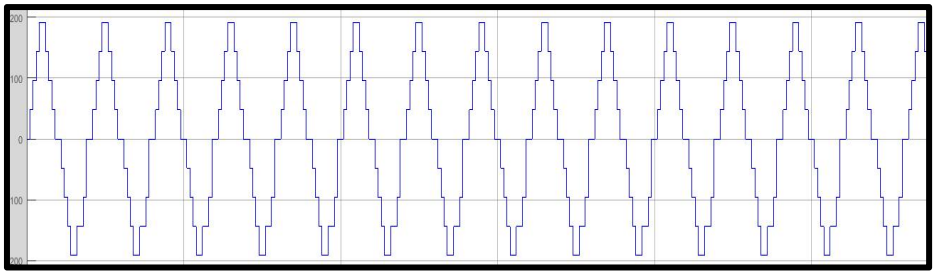


Fig. 5.6 Simulated output voltage waveform for RL load

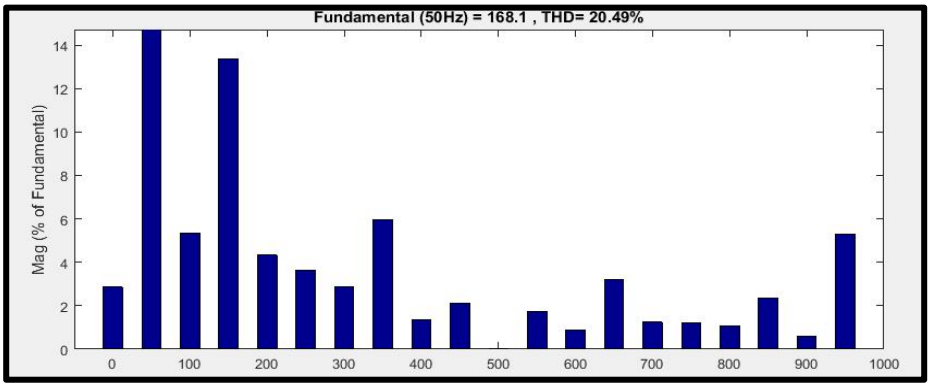


Fig. 5.7 FFT Analysis for simulated output Voltage waveform for RL load

Current

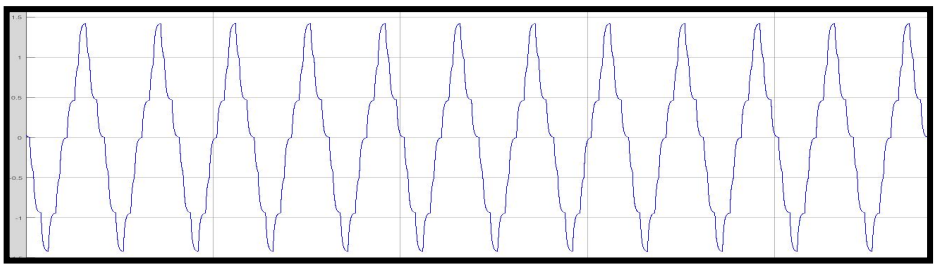


Fig. 5.8 Simulated output current waveform for RL load

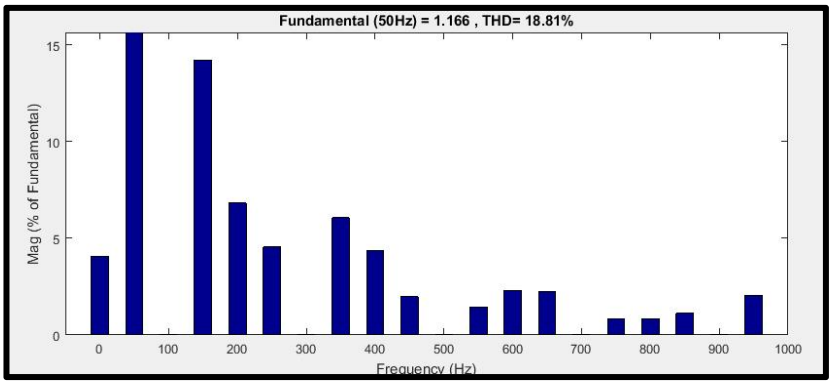


Fig. 5.9 FFT Analysis for simulated output current waveform for RL load

Table 5.3 Parameter values in open loop technique in RL load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	20.49%	18.41%	118.9V	0.820A	78 W	97.5 VA	0.8	80 %

5.1.2 Open loop PWM control technique.

Phase Shifted (PS-PWM)

Phase-shifted PWM (PSPWM) is a natural extension of traditional PWM techniques, specially conceived for FC and CHB converters. Since each FC cell is a two-level converter, and each CHB cell is a three-level inverter, the traditional bipolar and uni-polar PWM techniques can be used, respectively. Due to the modularity of these typologies, each cell can be modulated independently using the same reference signal. A phase shift is introduced between the carrier signals of contiguous cells, producing a phase-shifted switching pattern between them. In this way, when connected together, a stepped multilevel waveform is generated. It has been demonstrated that the lowest distortion can be achieved when the phase shifts between carriers are 180 or 360 degrees for a CHB or FC converter, respectively (where k is the number of power cells). This difference is related to the fact that the FC and CHB cells generate two and three levels, respectively. Since all the cells are controlled at the same reference and same carrier frequency, the switch device usage and the average power handled by each cell are evenly distributed. In the case of the CHB, this means that multi-pulse diode rectifiers can be used to reduce input current harmonics. For the FC, the advantage of the even power distribution is that once the flying capacitors are properly charged (initialized to their corresponding values), no unbalance will be produced due to the self-balancing property of this topology. Hence, there is no need to control the DC-link voltages. Another interesting feature is the fact that the total output voltage has a switching pattern with k times the frequency of the switching pattern of each cell. This multiplicative effect is produced by the phase-shifts of the carriers. Hence, better total harmonic distortion (THD) is obtained at the output by using k-times lower frequency carriers.

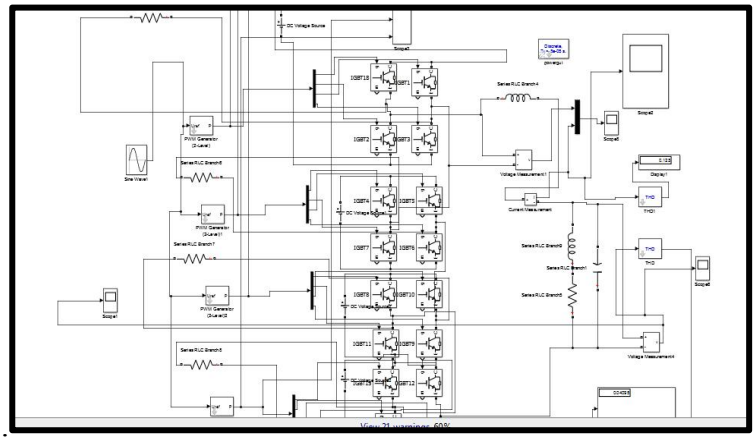


Fig. 5.10 Simulink diagram of open loop control method

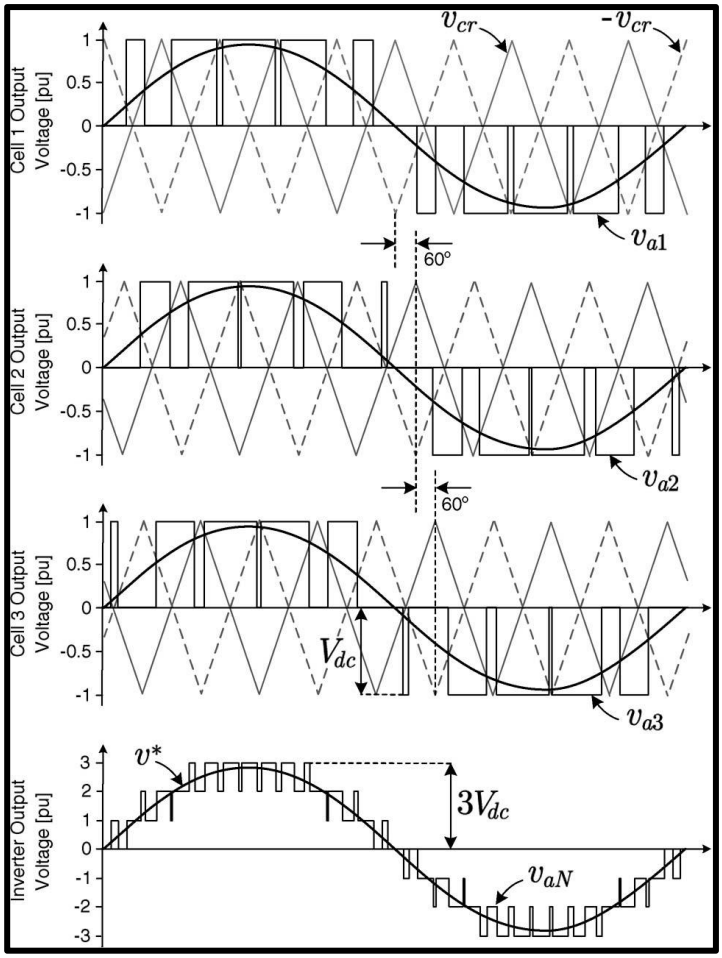


Fig. 5.11 Three-cell (seven-level) PS-PWM waveform generation for CHB.

Level Shifted (LS-PWM):

Level-shifted PWM (LSPWM) is the natural extension of bipolar PWM for multilevel inverters. Bipolar PWM uses one carrier signal that is compared to the reference to decide between two different voltage levels, typically the positive and negative busbars of a VSI. By generalizing this idea, for a multilevel inverter, m-1 carriers are needed. They are arranged in vertical shifts instead of the phase-shift used in PS-PWM. Each carrier is set between two voltage levels; hence the name "B-level shifted." . Since each carrier is associated with two levels, the same principle of bipolar PWM can be applied, taking into account that the control signal has to be directed to the appropriate semiconductors in order to generate the corresponding levels. The carriers span the whole amplitude range that can be generated by the converter. They can be arranged in vertical shifts, with all the signals in phase with each other, called phase disposition (PD-PWM); with all the positive carriers in phase with each other and in the opposite phase of the negative carriers, known as phase opposition disposition (POD-PWM); and alternate phase opposition disposition (APOD-PWM), which is obtained by alternating the phase between adjacent carriers. Figures 5.12 (a)–(c) show examples of these arrangements for a five-level inverter (thus four carriers). This modulation method is

especially useful for NPC converters since each carrier can be easily associated with two power switches of the converter. Figure 5.12(a) shows that when the value of the reference is greater than the value of both carriers, the upper switches are activated, connecting the load to the positive bus-bar. The output is connected to the neutral point N when the reference value is between both carriers (vcr2 – v-vcr1). Finally, at the times in which the reference value is lower than both carriers, the lower switches are turned on, connecting the load to the negative bus-bar.

LS-PWM leads to less distorted line voltages since all the carriers are in phase compared to PS-PWM. In addition, since it is based on the output voltage levels of an inverter, this principle can be adapted to any multilevel converter topology. However, this method is not preferred for CHB and FC since it causes an uneven power distribution among the different cells. This generates input current distortion in the CHB and capacitor unbalance in the FC compared to PS-PWM.

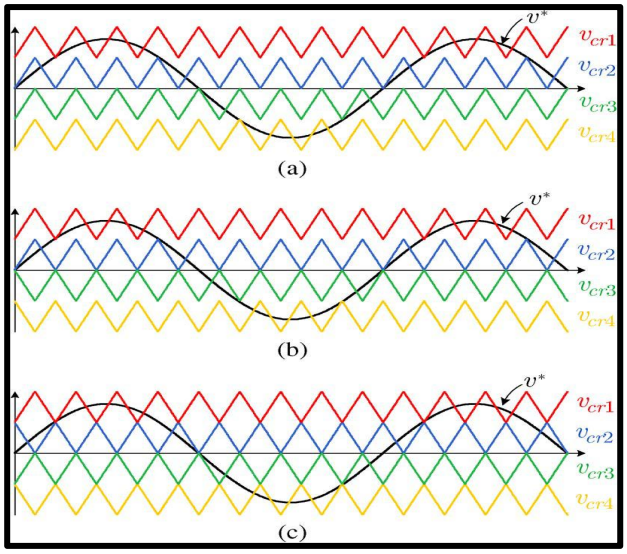


Fig. 5.12 LS-PWM carrier arrangements: (a) PD, (b) POD, and (c) APOD.

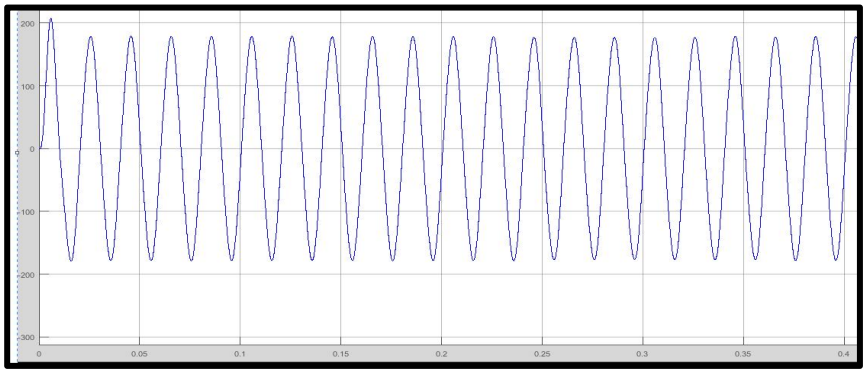


Fig. 5.13 Output voltage waveform in open loop PWM for R load

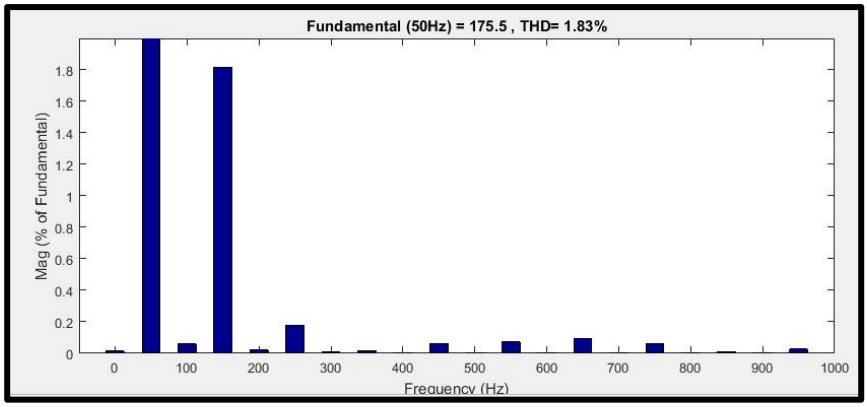


Fig. 5.14 FFT analysis of voltage waveform in open loop PWM for R load

Current

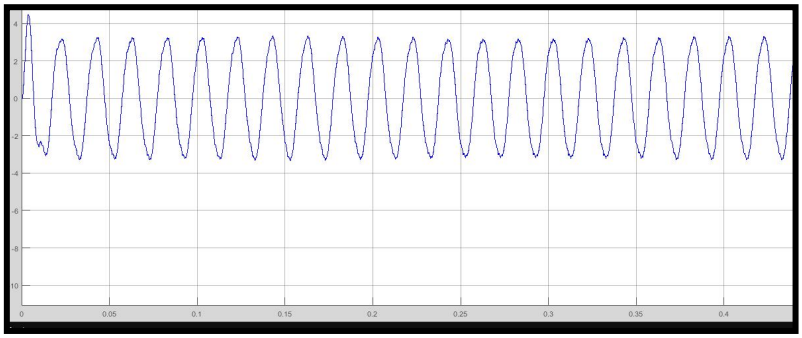


Fig. 5.15 Waveform for o/p current in open loop PWM for R load

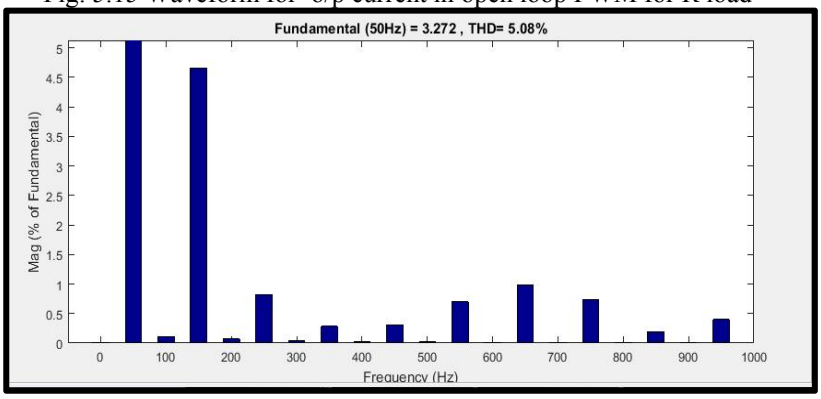


Fig. 5.16 FFT Analysis of o/p current in open loop PWM for R load

Table 5.4 Parameter values in open loop PWM technique with R load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	1.83%	5.08%	126.88V	2.35A	146.1W	298.168 VA	0.4899	76%

Voltage

Fig. 5.17 Output voltage waveform in open loop PWM for RL load

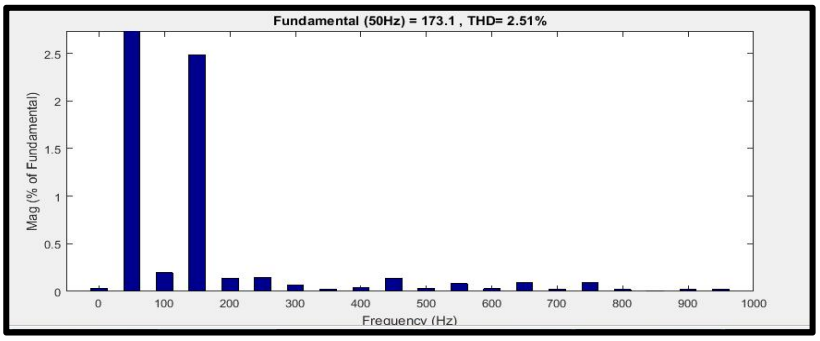


Fig. 5.18 FFT analysis of voltage waveform in open loop PWM for RL load

Current

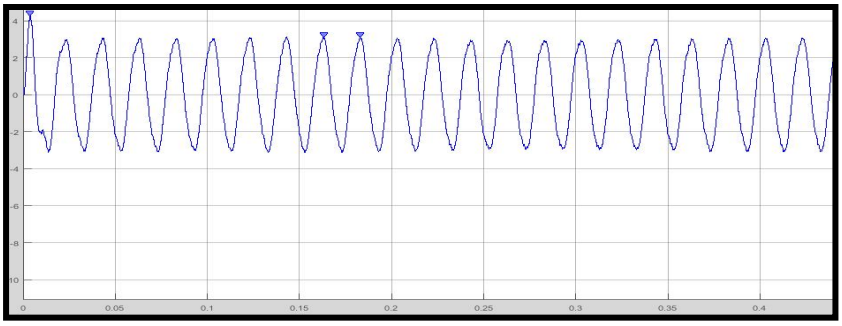


Fig. 5.19 Waveform for o/p current in open loop PWM for RL load

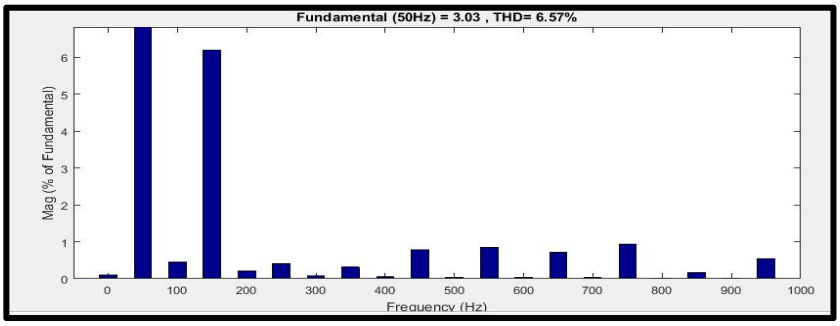


Fig. 5.20 FFT Analysis of o/p current in open loop PWM for RL load

Table 5.5 Parameter values in open loop PWM technique with RL load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.51%	6.57%	125.58V	2.211A	141.1W	277.657VA	0.508	74%

Table 5.6 comparison of different parameters in open loop techniques with R and RL load

Sr. No.		R load		RL load	
		Open Loop	Open Loop PWM	Open Loop	Open Loop PWM
1	RMS o/p voltage	134.37V	126.88V	118.9V	125.58V
2	RMS o/p current	1.41A	2.35A	0.820A	2.211A
3	Active Power	171.05W	146.1W	78W	141.1W
4	Apparent Power	190.05VA	298.16VA	97.5VA	277.65VA
5	Power factor	0.9	0.4899	0.8	0.508
6	THD in voltage	18.48%	1.83%	20.49%	2.51%
7	THD in current	18.20%	5.08%	18.41%	6.57%
8	Efficiency	84%	76%	80%	74%

5.2 Contribution-2: Simulation and comparison of closed loop controlling Methods R , RL and motor loads.

There are closed loop techniques need to be employed to obtain the minimum error . The purpose of using closed loop technique is to obtain the value of controlled parameter to the set value. In order to attain minimum THD in output voltage and output current following techniques are simulated and results are compared.

1. Closed loop PWM control technique using PID
2. ANN based closed loop based technique
3. Fuzzy logic controller based closed loop technique

5.2.1 Closed loop PWM technique using PID

A reference signal of 200 V, 50 Hz is applied to obtain a constant output voltage of 200 V peak and 50 Hz frequency. The output voltage signal is compared with the reference signal to generate an error signal e (t). The error signal is applied to the PID controller. The output of the PID controller is applied as a reference signal to the PWM generators. PWM generators are used to generate the gating pulses to trigger the switches

in a multilevel converter. The values of total harmonic distortion in output voltage and current are obtained and noted down. The values of K_p and K_d used in the PI controller are 0.1 and 0.01 respectively. The PI controller is tuned and the above values of K_p and K_d are obtained.

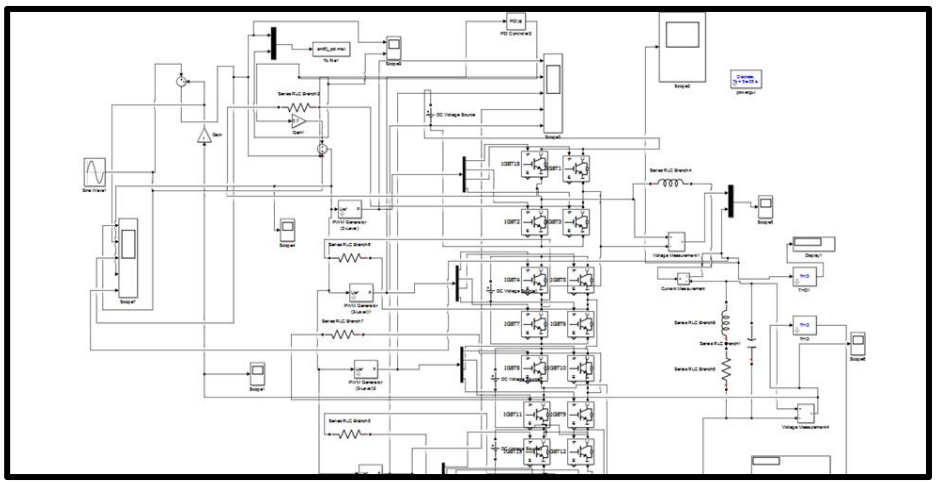


Fig. 5.21 Simulation diagram of closed loop PWM technique using PID

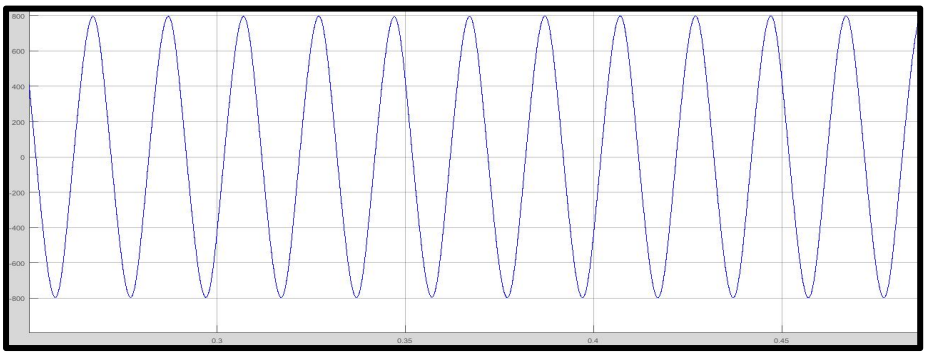


Fig. 5.22 Simulated output voltage waveform for closed loop PID method for R load

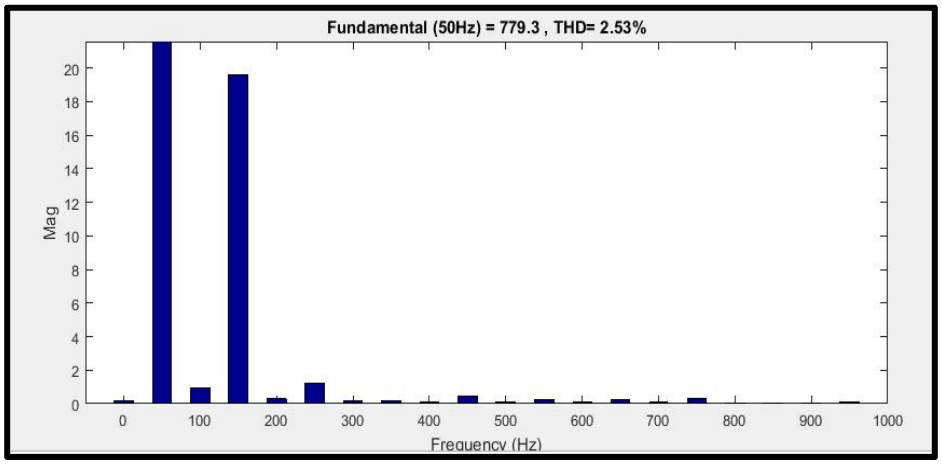


Fig. 5.23 FFT Analysis of simulated output voltage waveform for closed loop PID for R load

Current

Fig. 5.24 FFT Analysis of simulated output current waveform for closed loop PID method for R load

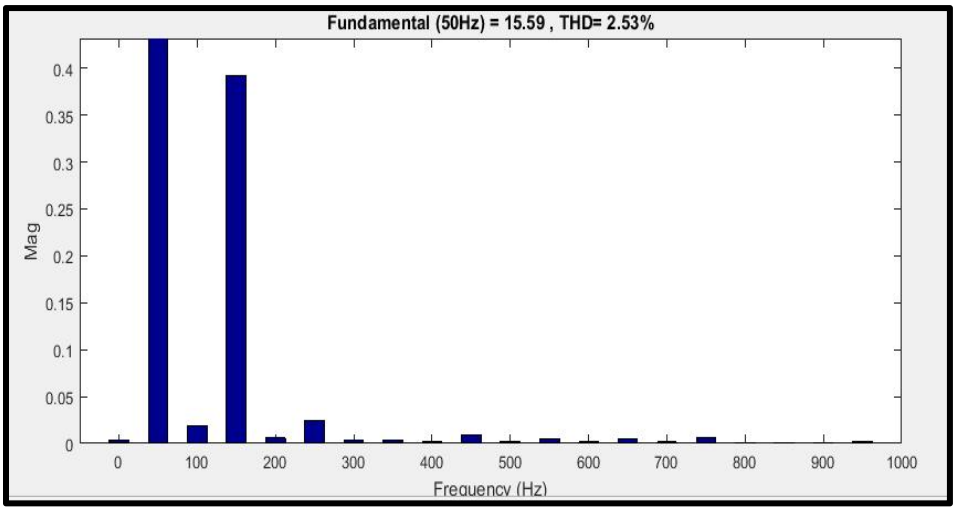


Fig. 5.25 FFT analysis of output current waveform for closed loop PID method for R load

Table 5.7 Parameter values in closed loop PID technique for R load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.55%	2.55%	565.7V	10.61 A	6000W	6000VA	1	94%

Voltage

Fig. 5.26 Simulated output voltage waveform in closed loop PID method for RL load

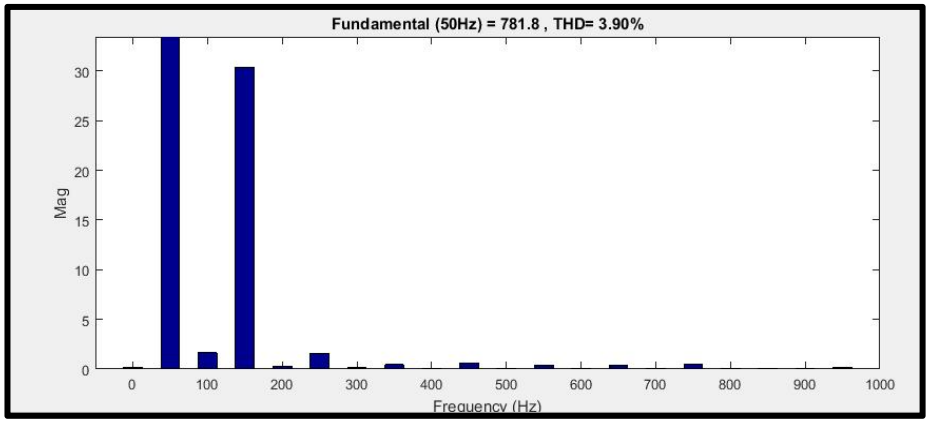


Fig. 5.27 FFT Analysis of simulated output voltage waveform in closed loop PID for RL load

Current

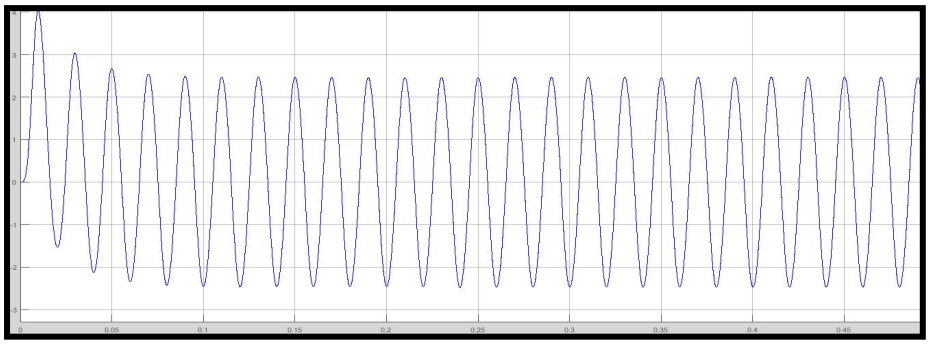


Fig. 5.28 Output current waveform in closed loop PID method for RL load

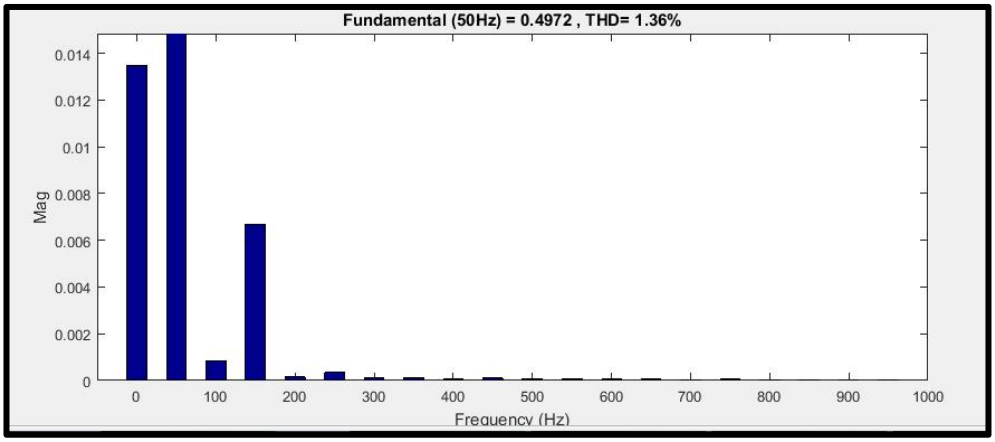


Fig. 5.29 FFT analysis of output current waveform with PID for RL load

Table 5.7 Parameter values in closed loop PID technique for RL load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
values	3.90%	1.56%	567.7V	1.73A	942.816	982.1VA	0.96	92%

Voltage

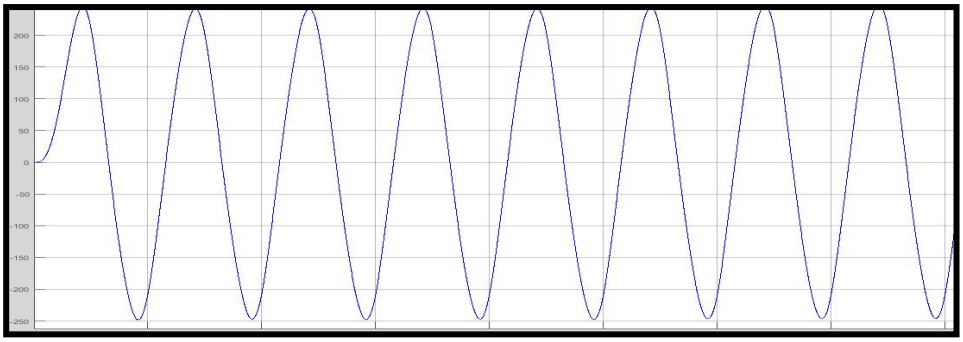


Fig. 5.26 Simulated output voltage waveform in closed loop PID method for motor load

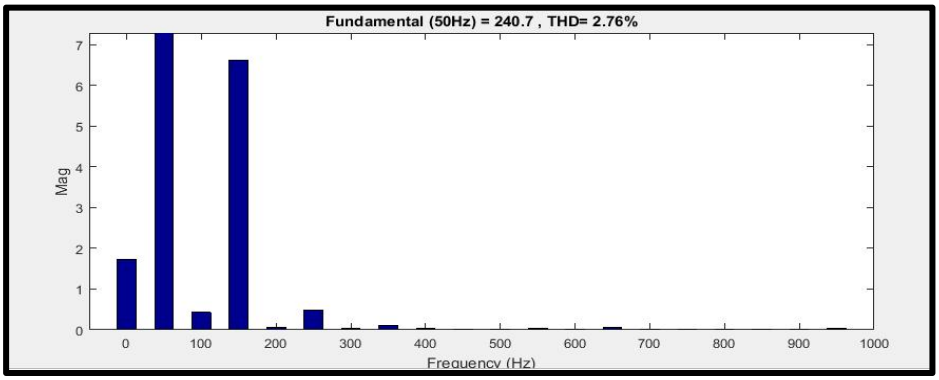


Fig. 5.27 FFT Analysis of simulated output voltage waveform in closed loop PID method for motor load

Current

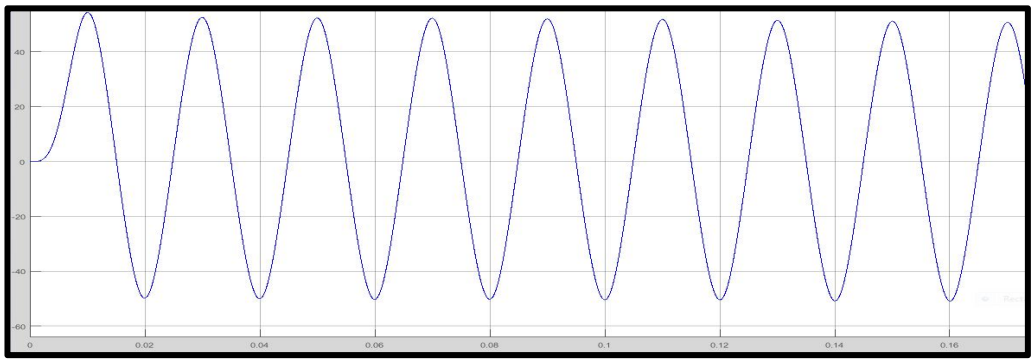


Fig. 5.28 Output current waveform in closed loop PID method for motor load

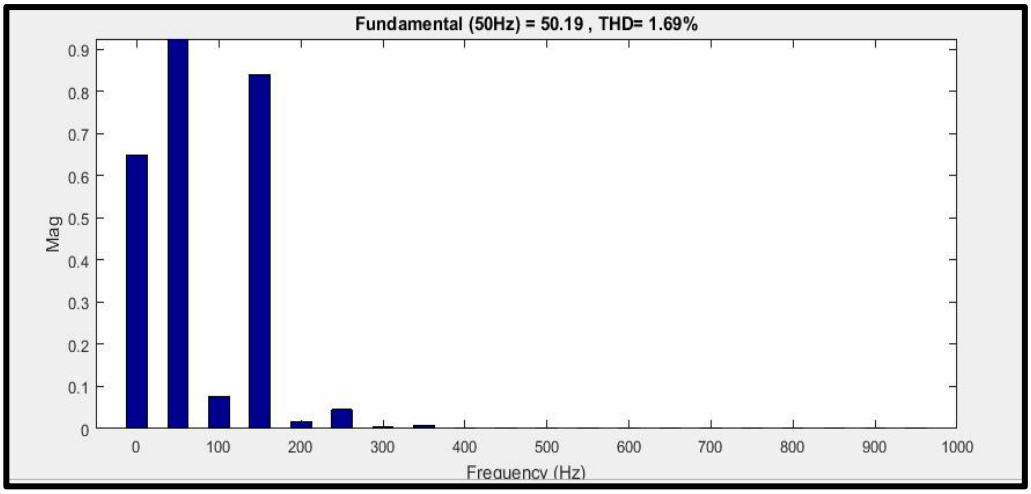


Fig. 5.29 FFT analysis of output current waveform with PID for motor load

Table 5.7 Parameter values in closed loop PID technique for motor load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
values	2.76%	1.69%	176.75	36.92	6264.58	6525.61	0.96	90%

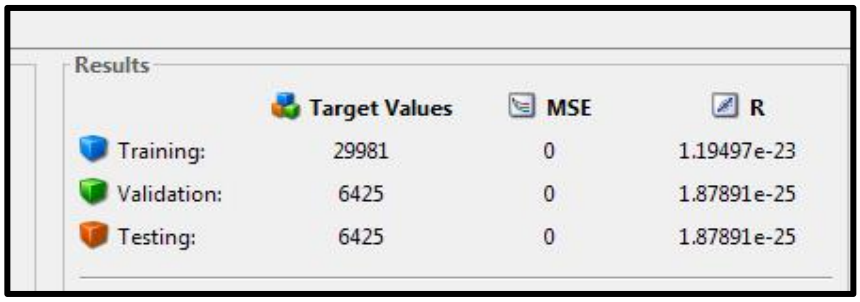
5.2.2 ANN based Closed loop PWM technique.

Simulations are carried out using MATLAB Simulink. The purpose of using MATLAB simulation is to ensure that the switches used are incorporated with snubber circuits. The on-state resistance across the power devices is considered as in the case of practical situations. Add-on hardware can be incorporated and can be used as a subsystem. In this research work, we carried out two different simulations. One simulation is with the P-I controller and one with the use of the ANN controller replacing the P-I controller. The values of K_p and K_i that are used in the simulation are fixed after the number of trials. From the simulated output waveform of current and voltage, the value of THD is obtained using FFT analysis. The difference in the THD values obtained is tabulated. The data samples are collected and stored in an a.mat file. 70% of data samples are used to train the ANN block. 15% of data samples are not used. The remaining 15% of data samples are tested. A PWM generator block with internal generation of carrier signal with a very high value of carrier frequency in the order of 27*50 Hz is used. The signal of peak 200V and 50 Hz frequency is used as a reference signal to generate the error signal. A voltage source of 50 V is applied as a dc input voltage to each cascaded H-bridge circuit. The performance of the ANN based cascaded H-bridge nine level inverter with isolated dc sources is determined through MATLAB/Simulink software. A filter is used at the output of

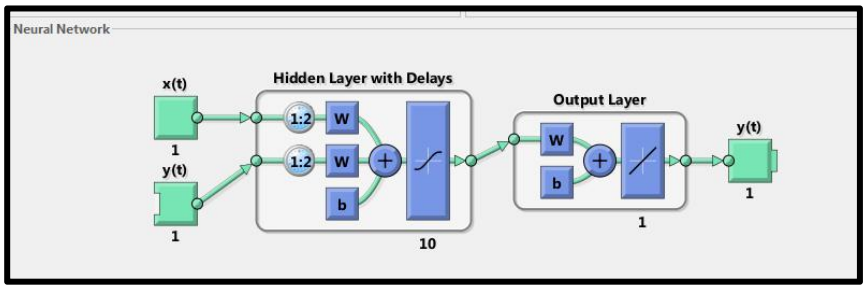
the inverter to reduce the ripples. The simulation parameters used in the simulation are tabulated in table 1. The simulation without ANN and with ANN is carried out for comparison.

The ANN structure formed is trained with 29881 samples. The samples are obtained with simulation of PID controller technique. The training is done by L-M and B-R algorithms. Out of the two algorithms L-M algorithm gives minimum error. The problem definition is given by

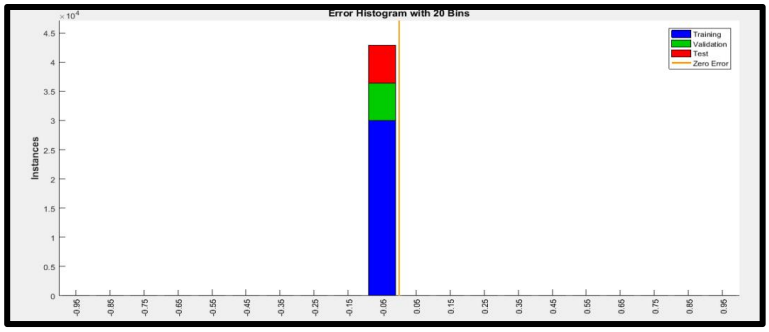
$$Y(t)=f(x(t-1)\ldots\ldots x(t-d),y(t-1)\ldots\ldots y(t-d))\text{----------}(5.1)$$



(a)



(b)



(c)

Fig. 5.30 (a) ANN layers (b)Data samples (c)Error Histogram

The modulation index, which is the ratio of the peak of the modulating signal to the peak of the carrier signal, can be adjusted with the help of a selected PWM generator block, and THD can be adjusted. In our

research work, it is set to a value of 0.8. The phase delay for each converter can be changed with the setting in the PWM generator block. The total of 180 degrees in each half cycle is divided among four cascaded H-bridge circuits. The nature of the output voltage waveform is decided by the selection of the parameters of the PWM block. THD and ripples are reduced in the output voltage. As a result, the efficiency of the DC to AC conversion is increased. With the help of neural networks, it is possible to deliver very high voltage and good quality of power with fewer harmonics with the help of a multilevel converter.

The use of ANN also results in the permission of the use of smaller filters across the load. The resistive-inductive loads are connected across the cascaded H-bridge nine-level inverter. The output voltage remains constant at the reference value. The total harmonic distortion in voltage is 3.70%. The total harmonic distortion in the current waveform is 1.36% with the PI controller, whereas with the help of ANN, the THD content in the voltage and current waveform is reduced to 2.96% and 1.00%, respectively.

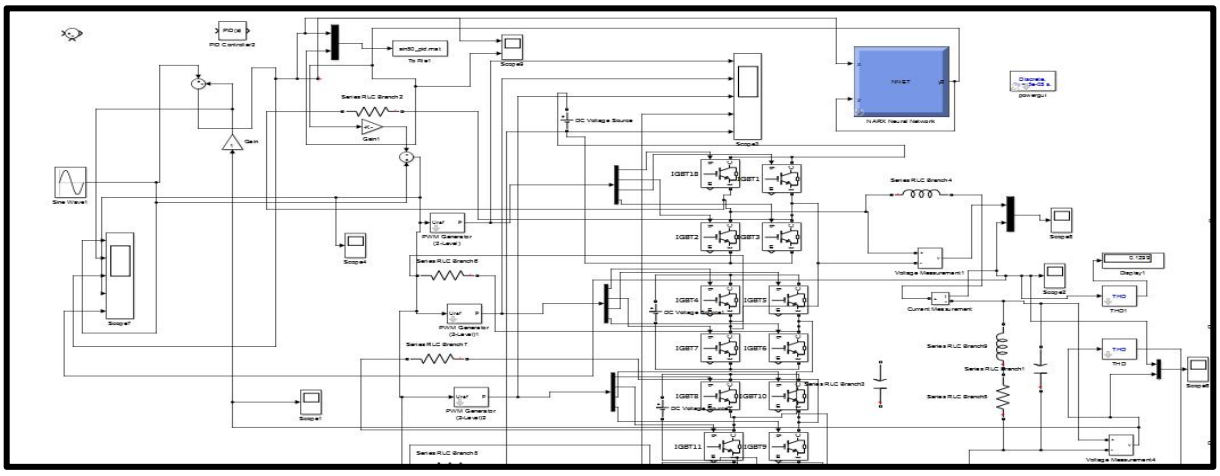


Fig. 5.31 ANN based closed loop Multilevel converter

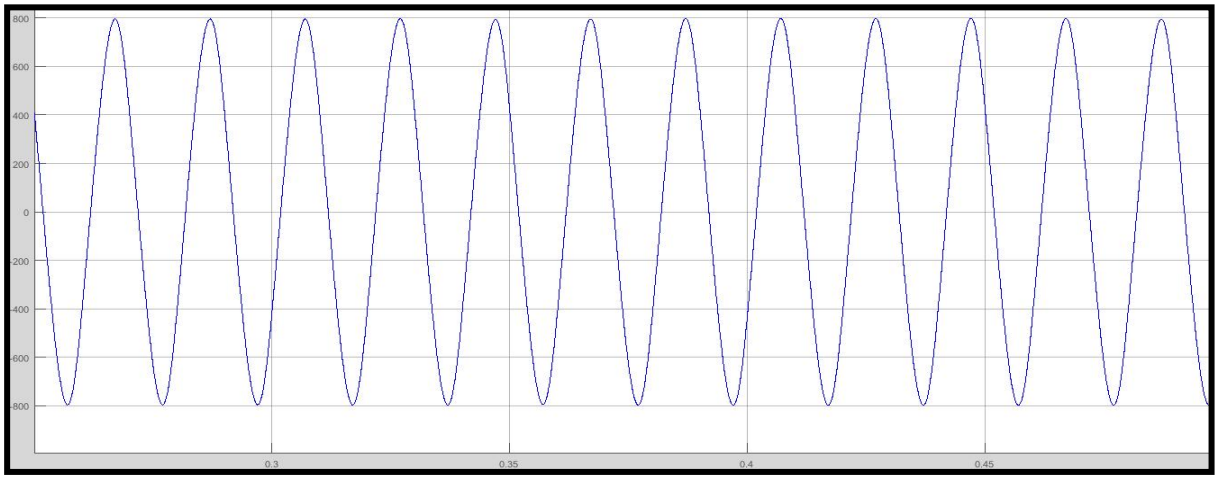


Fig. 5.32 Output voltage waveform with ANN based closed loop method with R load

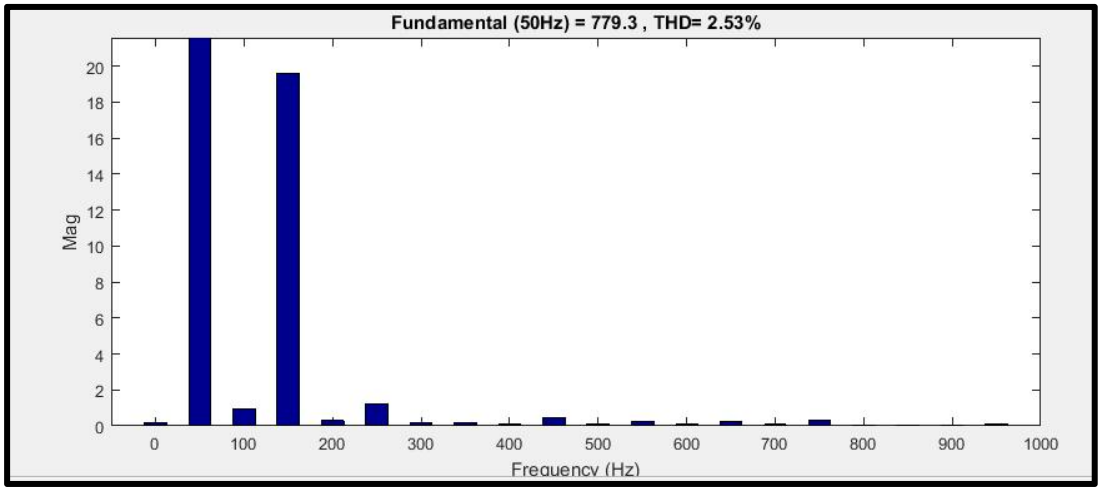


Fig. 5.33 FFT analysis of output voltage waveform with ANN based closed loop method with R load

Current

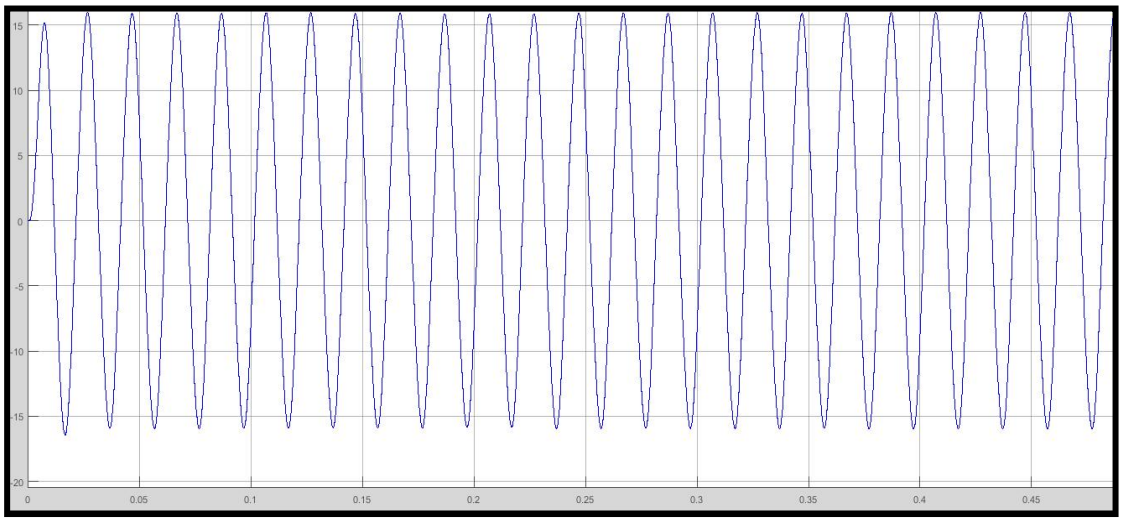


Fig. 5.34 Output current waveform with ANN based closed loop method with R load

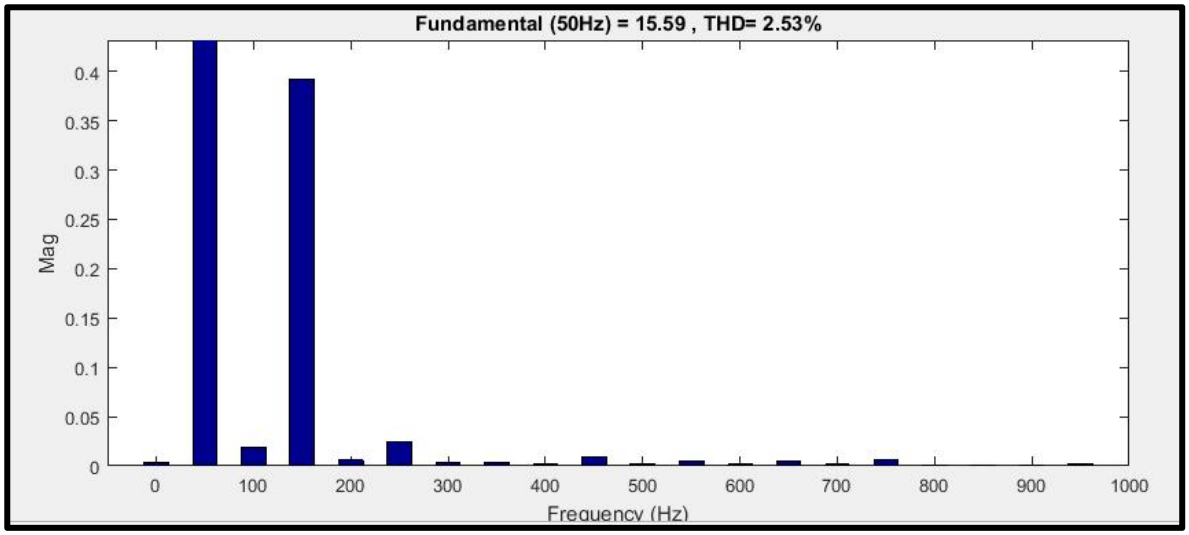


Fig.5.35 FFT analysis of output current waveform with ANN based closed loop method with R load

Table 5.8 Parameter values in ANN based closed loop method for R load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.53%	2.53%	565.69V	11.31	6400W	6400VA	1	96%

Voltage

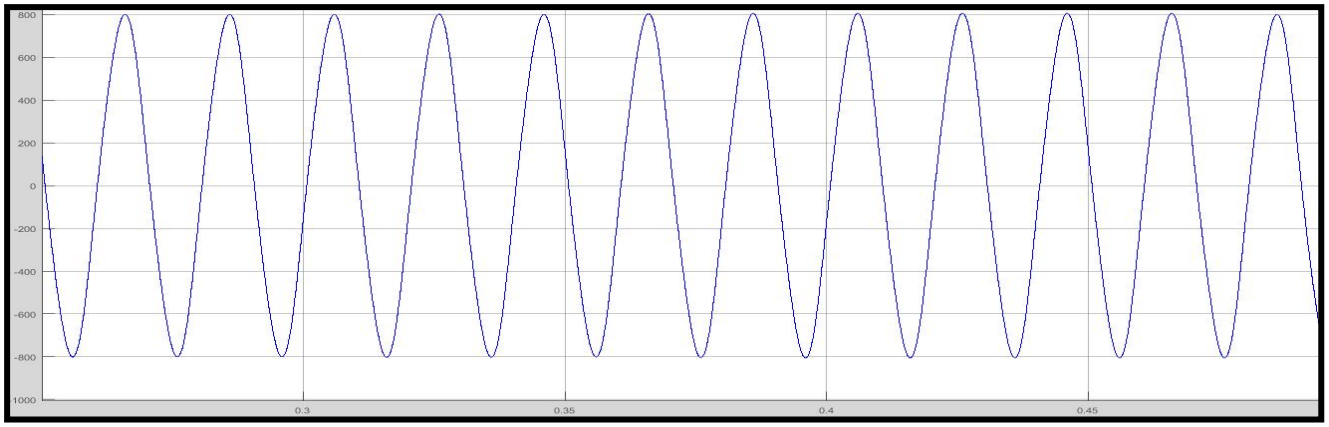


Fig. 5.36 Simulated output voltage waveform for ANN based closed loop method with RL load

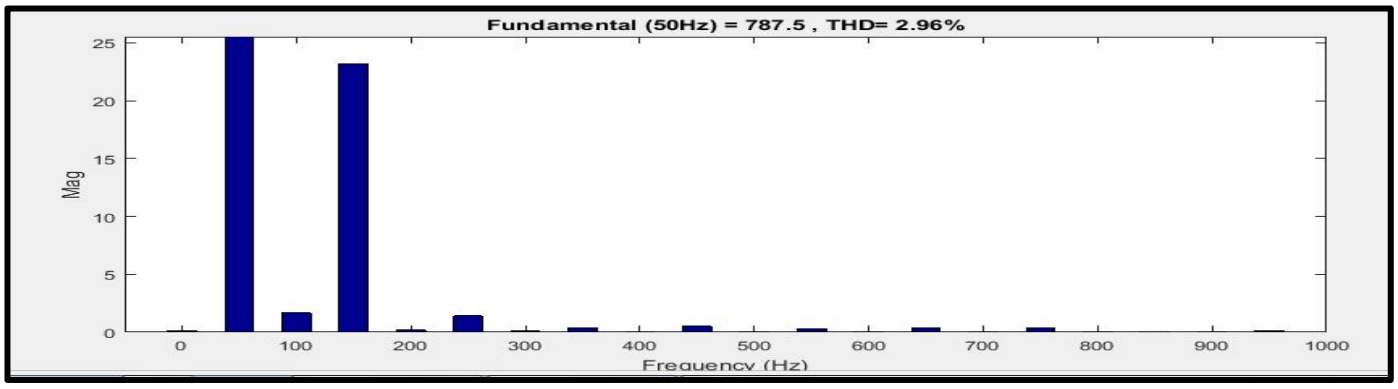


Fig. 5.37 FFT analysis of output voltage waveform for ANN based closed loop method with RL load

Current

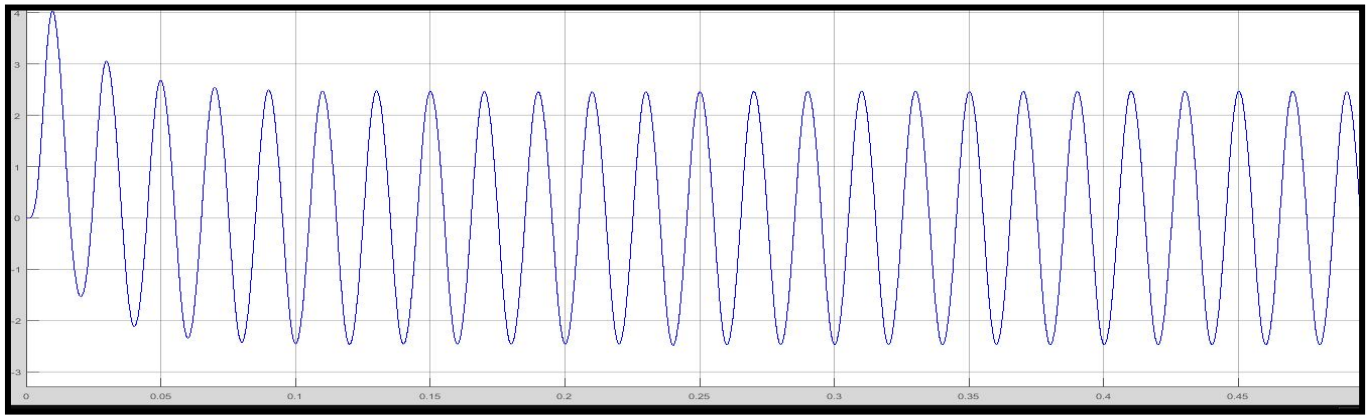


Fig. 5.38 Simulated output current waveform for ANN based closed loop method with RL load

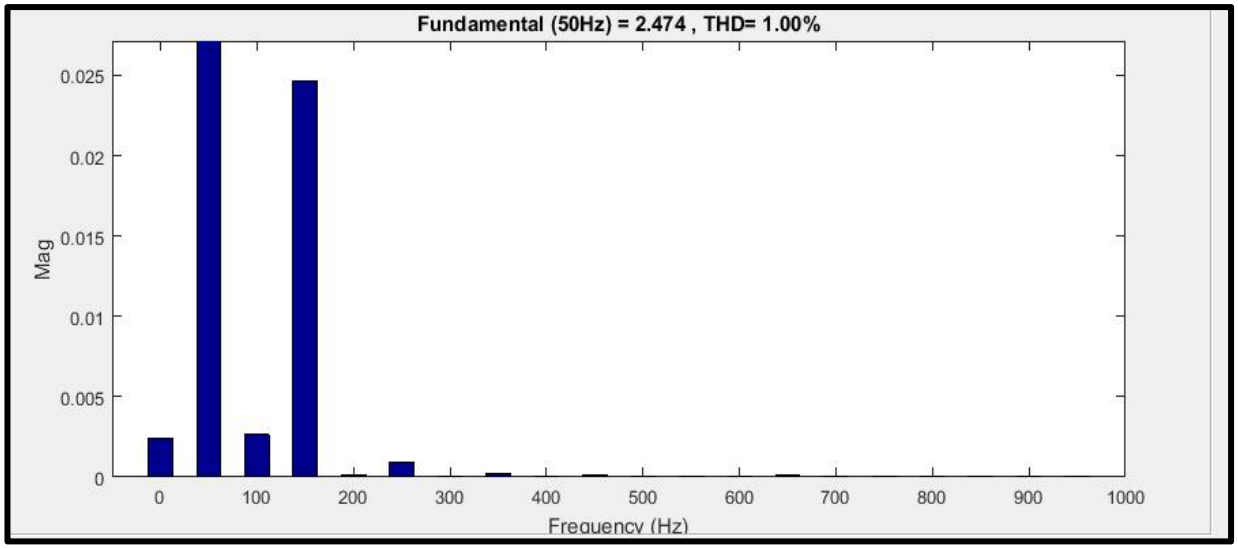


Fig. 5.39 FFT analysis of output current waveform for ANN based closed loop method with RL load

Table 5.9 Parameter values in ANN based closed loop methods for RL load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.96%	1.00%	565.69V	1.75A	881.06W	989.96VA	0.89	94%

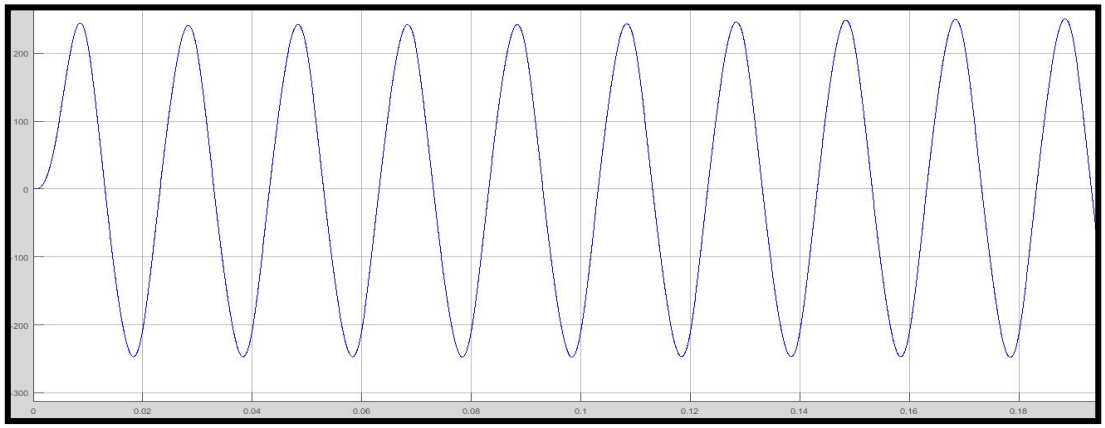


Fig. 5.40 Simulated output voltage waveform for ANN based closed loop method with motor load

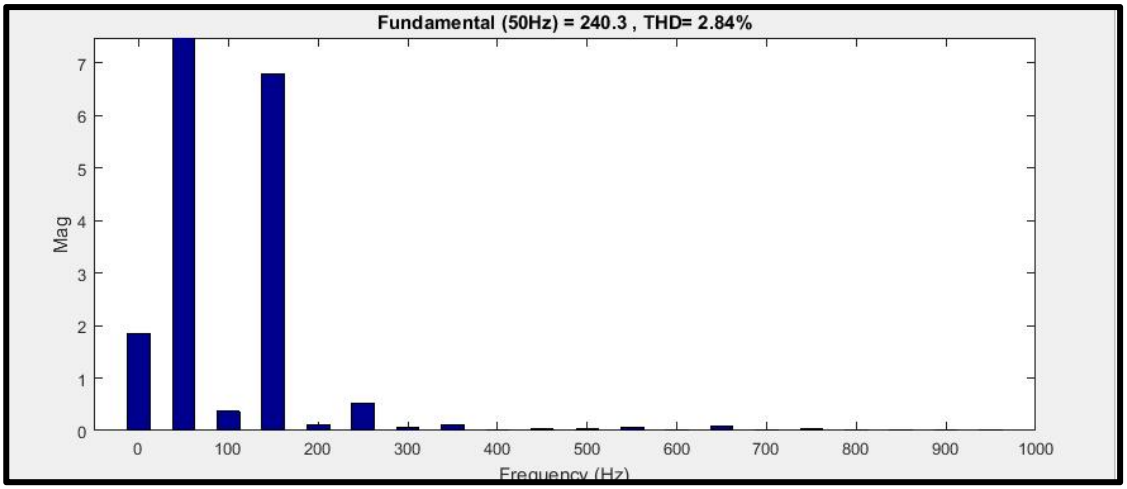


Fig. 5.41 FFT analysis of output voltage waveform for ANN based closed loop method with motor load

Voltage

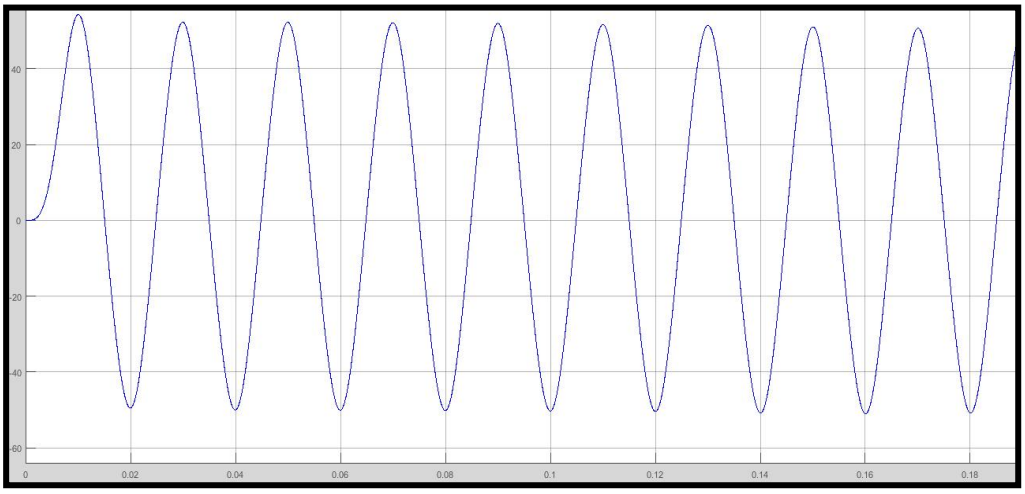


Fig. 5.42 Output current waveform for ANN based closed loop method with motor load

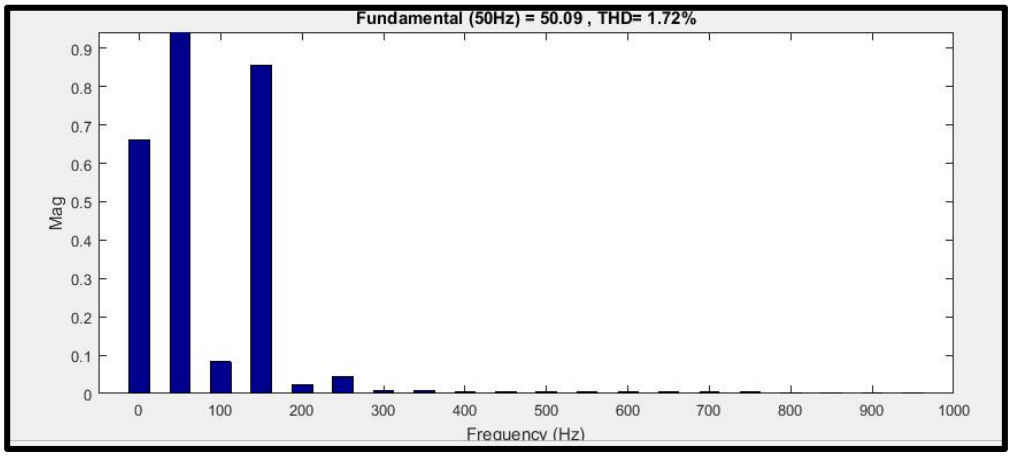


Fig. 5.43 FFT analysis of output current waveform for ANN based closed loop method with RL load

Table 5.9 Parameter values in ANN based closed loop methods for motor load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.84%	1.72%	176.77V	36.94A	6334W	6529.88	0.97	92%

5.2.3 Fuzzy logic controller based closed loop PWM technique.

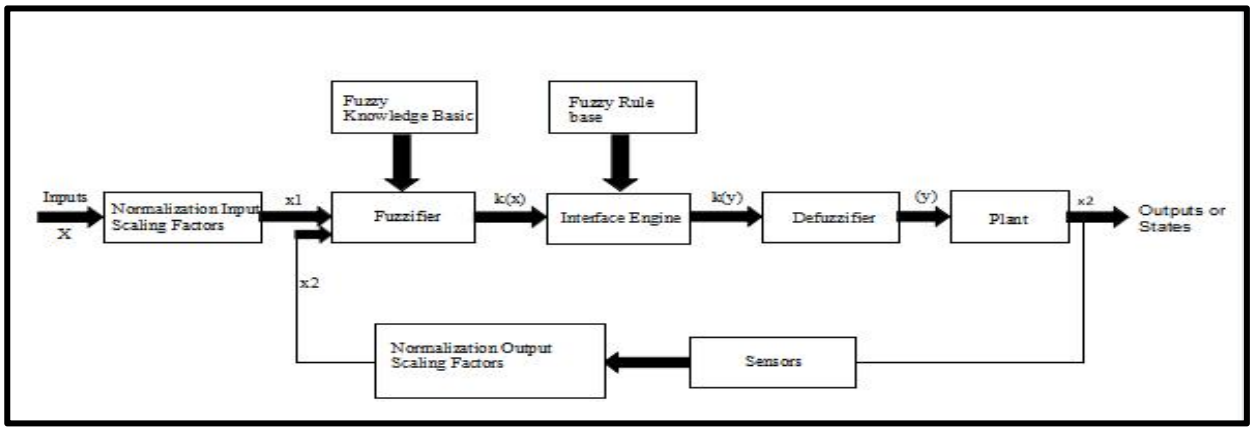


Fig.5.44 Basic architecture of a FLC System

The Fuzzy logic controller is adaptive in nature to operate in closed loop environment without any mathematical model. The Phase Disposition (PD) Pulse Width Modulation (PWM) technique used for generating triggering pulses to the switches in the Inverter. The out RMS voltage is compared with the reference value to generate error. Mamdani type Fuzzy Logic Controller (FLC) is used for control operation according to the error value.

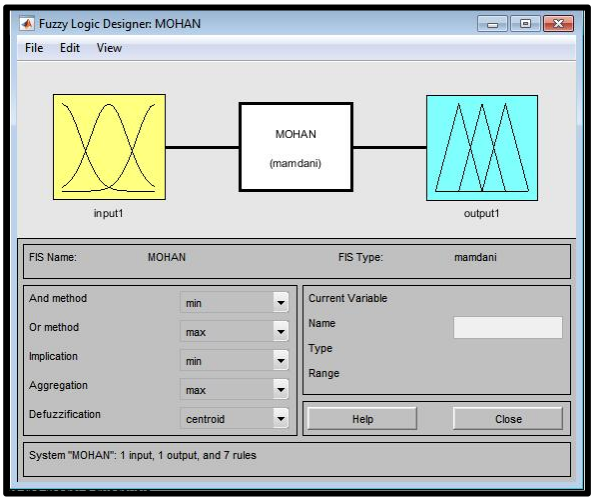


Fig.5.45 Fuzzy logic controller specifications

Input parameter range is set to -100 to 150,Output parameter range is set to - -0.15 to 0.2. We used 7 functions named EL- Trapezoidal, VL-Traingular, L-Trangular, N-Triangular, H-Triangular, VH-

Triangular, EH-Trapezoidal.

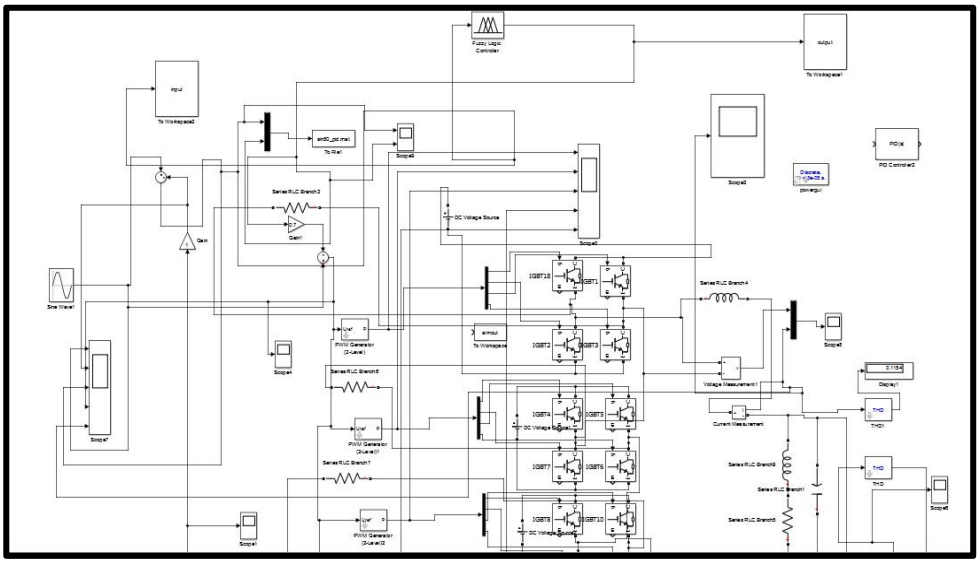


Fig. 5.46 Matlab simulation diagram using Fuzzy logic controller

Voltage

Fig. 5.47 Output voltage waveform with fuzzy logic controller based closed loop method with R load

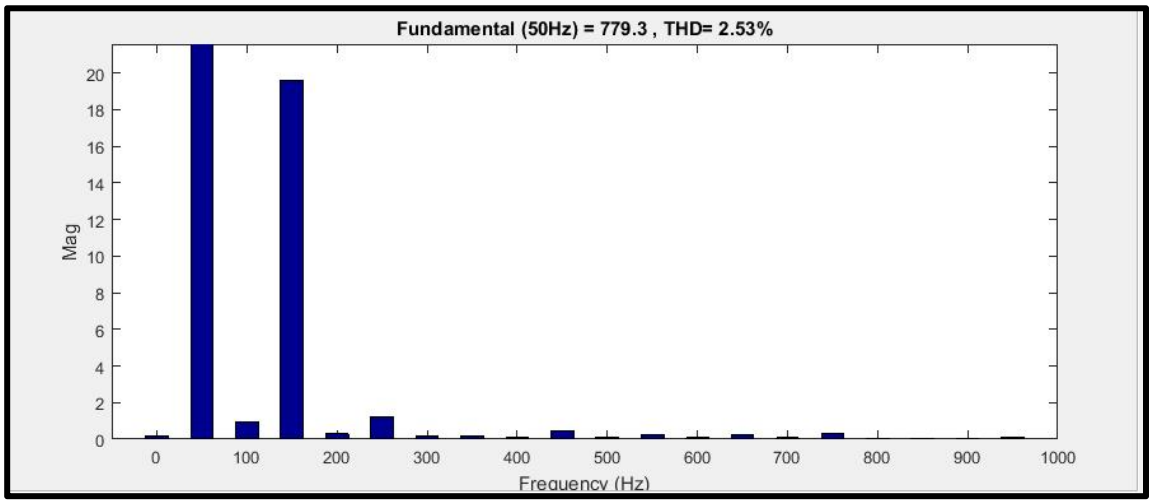


Fig. 5.48 FFT analysis of output voltage waveform for fuzzy logic controller based closed loop method with R load

Current

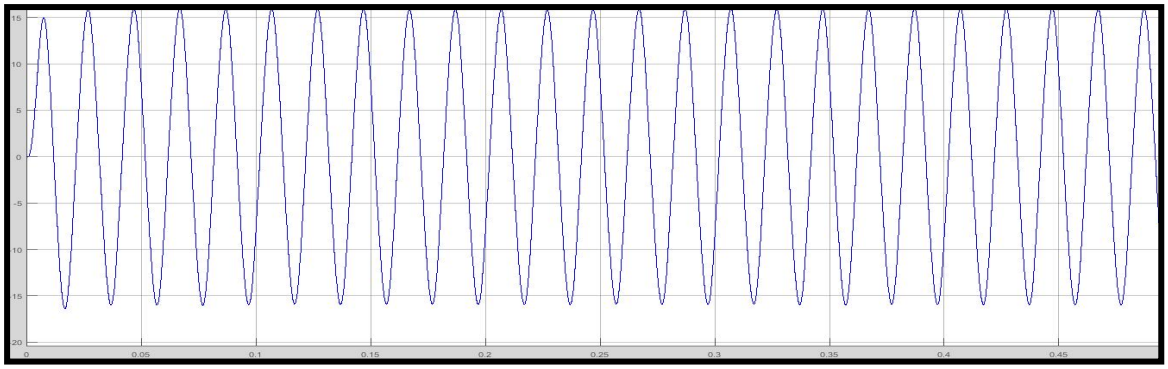


Fig. 5.49 Output current waveform for fuzzy logic controller based closed loop method with R load

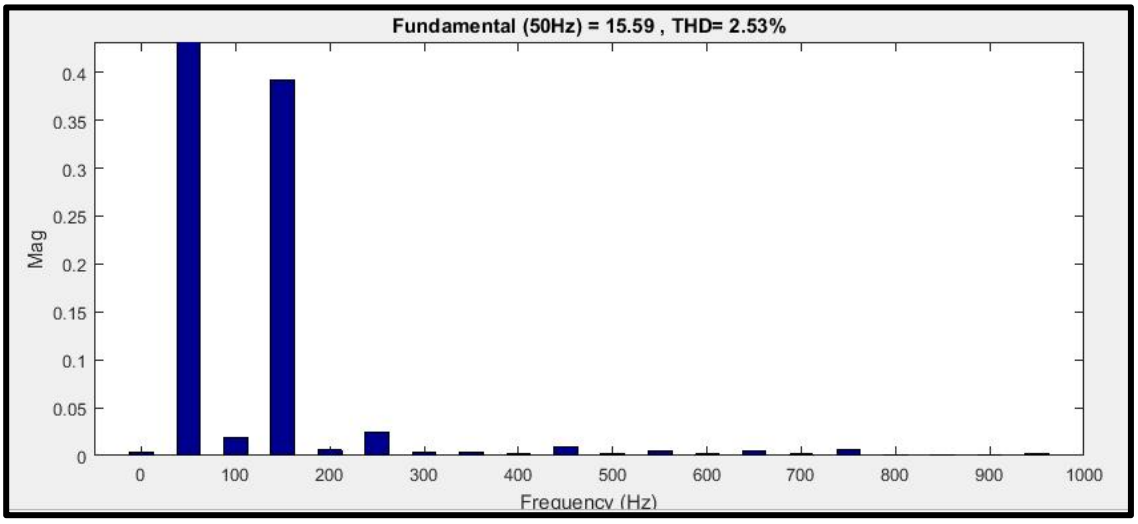


Fig. 5.50 FFT analysis of output current waveform for fuzzy logic controller based closed loop method with R load

Table 5.10 Parameter values in Fuzzy logic controller based closed loop method with R load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.53%	2.53%	566	11.31A	6401W	6401VA	1	96%

Voltage

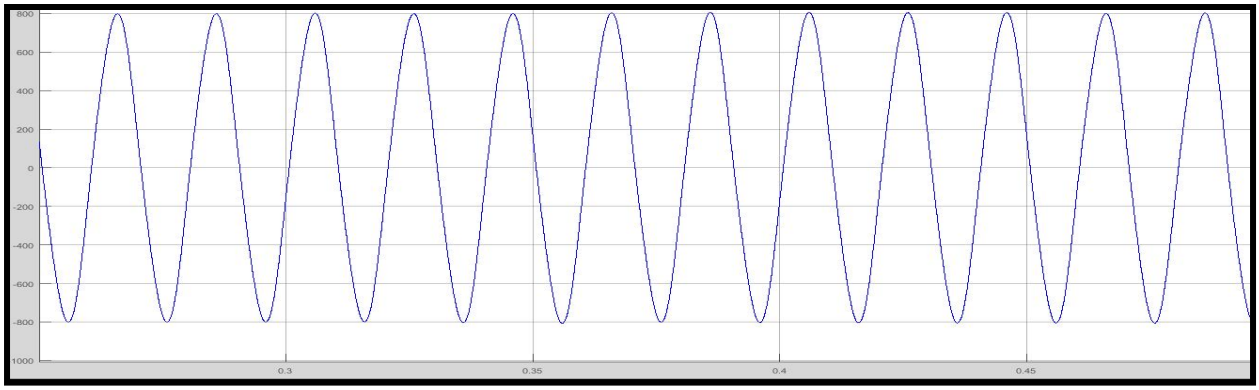


Fig. 5.51 Output voltage waveform for fuzzy logic controller based closed loop method with RL load

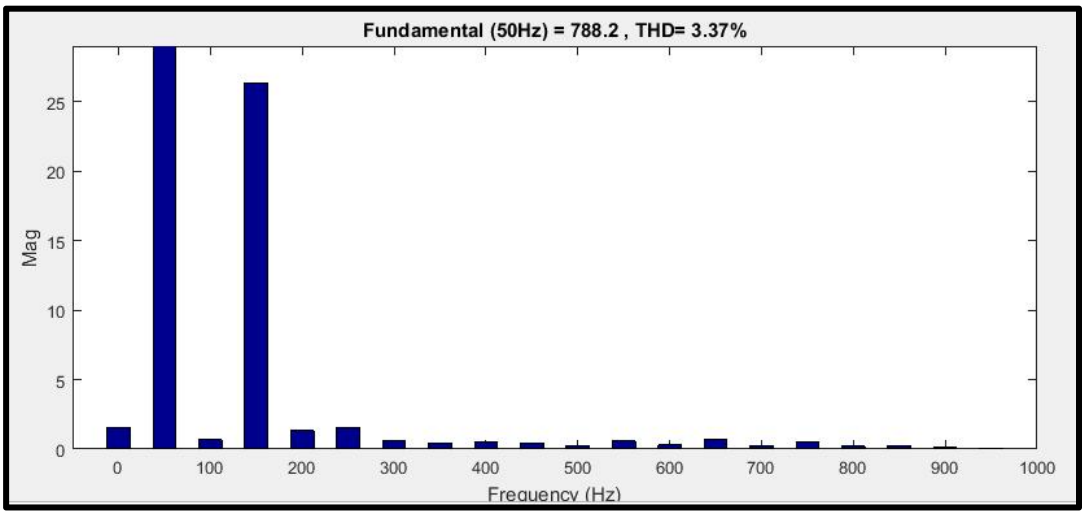


Fig. 5.52 FFT analysis of output voltage waveform with Fuzzy logic controller based closed loop method with RL load

Current

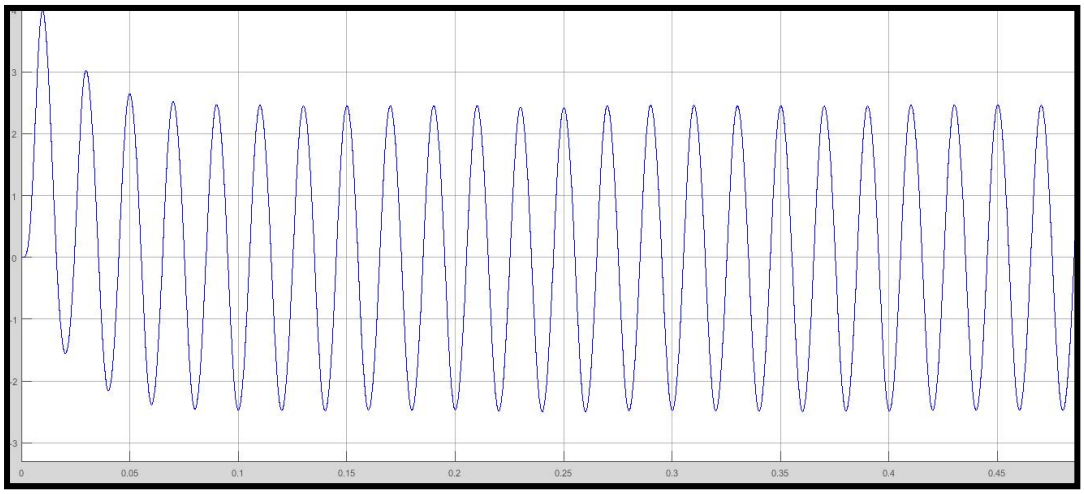


Fig. 5.53 Output current waveform for fuzzy logic controller based closed loop with RL load

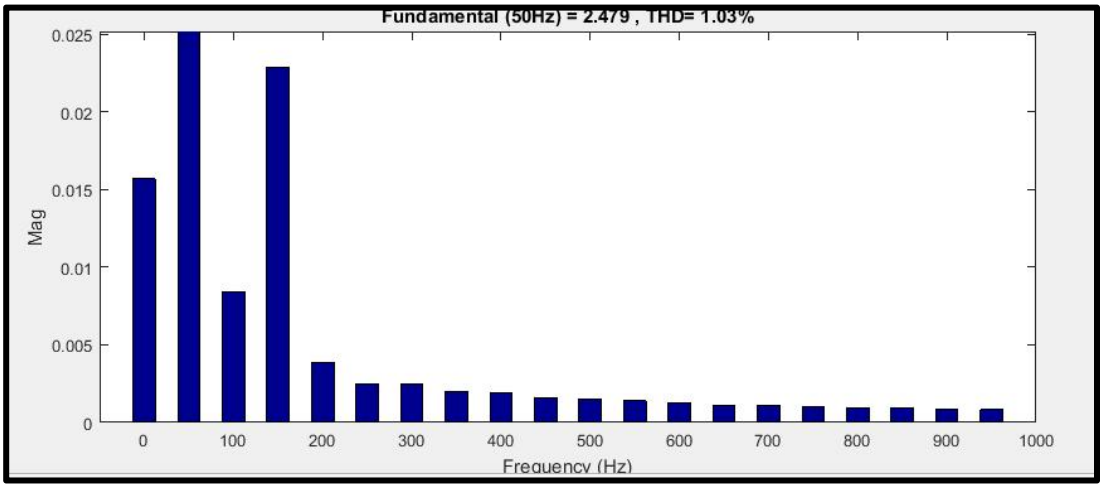


Fig. 5.54 FFT analysis of output current waveform for fuzzy logic controller based closed with RL load

Table 5.11 Parameter values in Fuzzy logic controller based closed loop method with RL load

Parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	3.37%	1.03%	565V	1.77A	870W	1000VA	0.87	94%

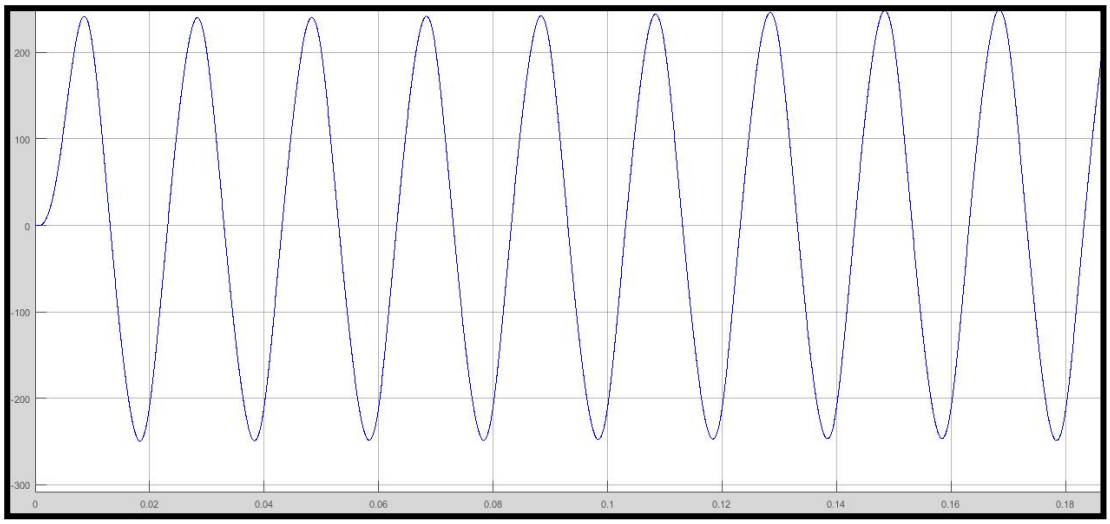


Fig. 5.55 Output voltage waveform for fuzzy logic controller based closed loop with motor load

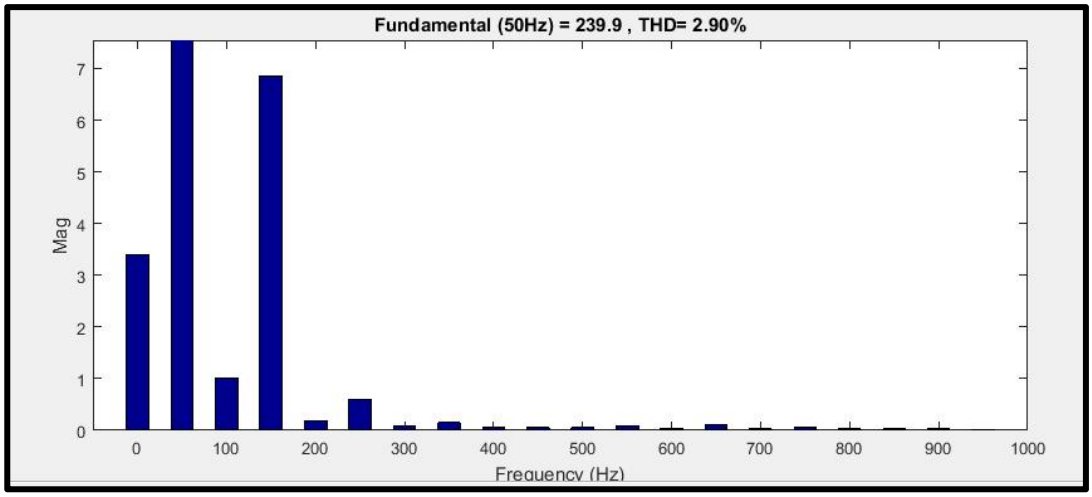


Fig. 5.56 FFT analysis of output voltage waveform for fuzzy logic controller based closed with motor load

Current

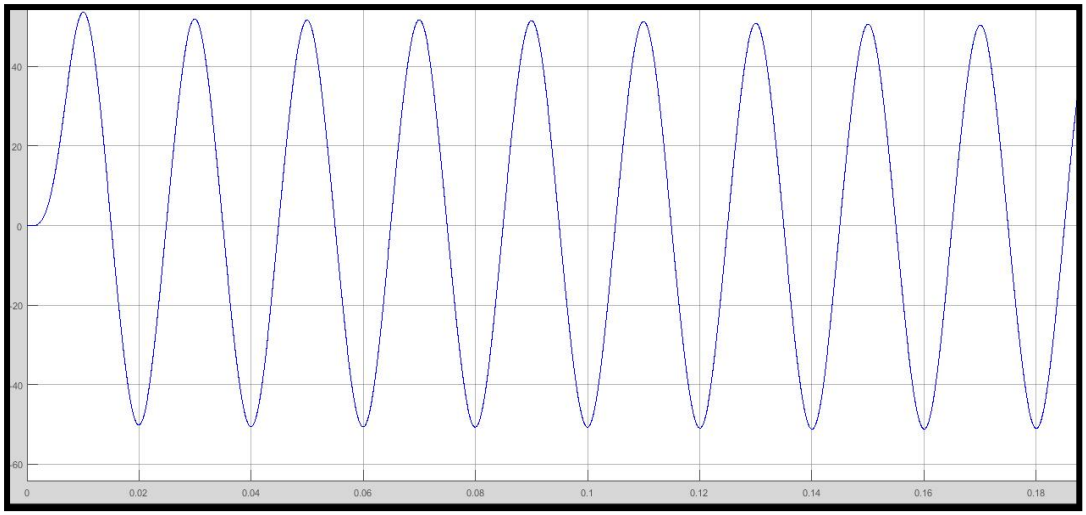


Fig. 5.57 Output current waveform for fuzzy logic controller based closed loop with motor load

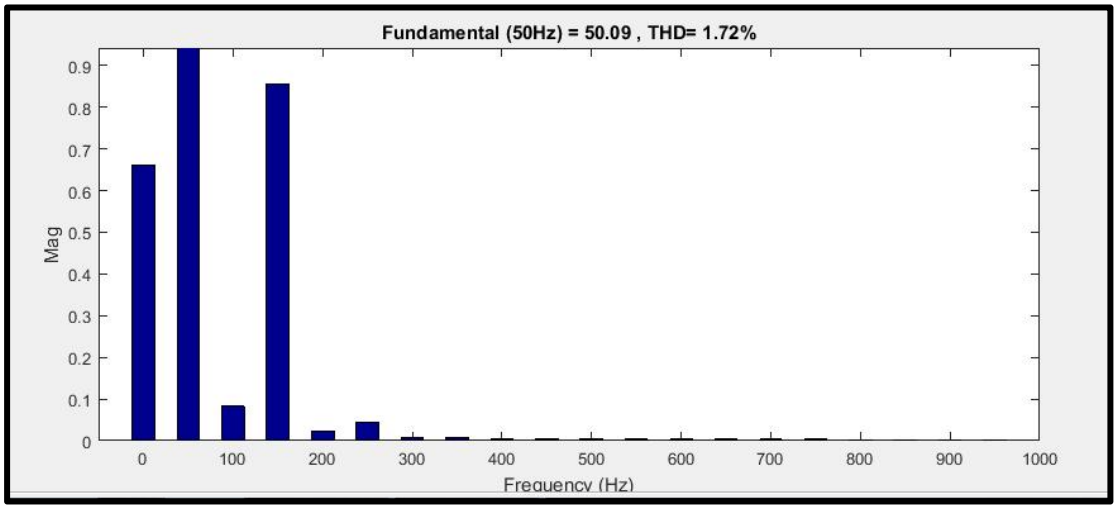


Fig. 5.58 FFT analysis of output current waveform with Fuzzy logic controller based closed with motor load

Table 5.10 Parameter values in Fuzzy logic controller based closed loop method with motor load

parameter	THD in voltage	THD in current	RMS o/p voltage	RMS o/p current	Active power	Apparent power	Power factor	Efficiency
Values	2.90%	1.72%	169.73	36.52A	6012W	6198.5VA	0.97	92%

Table 5.12 Comparison of different implemented closed loop control techniques in the form of different parameters with R load

Sr. No.	Parameter	Closed loop PID	Closed loop ANN	Closed loop Fuzzy
1	THD in voltage	2.55%	2.53%	2.53%
2	THD in current	2.55%	2.53%	2.53%
3	RMS o/p voltage	565.7V	565.69V	566
4	RMS o/p current	10.61A	11.31A	11.31
5	Active Power	6000W	6400W	6401W
6	Apparent Power	6000VA	6400VA	6401VA
7	Power factor	1	1	1
8	Efficiency	94%	96%	96%

Table 5.13 Comparison of different implemented closed loop control techniques in the form of different parameters with RL load

Sr. No.	Parameter	Closed loop PID	Closed loop ANN	Closed loop Fuzzy logic controller
1	THD in voltage	3.90%	2.96%	3.37%
2	THD in current	1.56%	1.00%	1.03%
3	RMS o/p voltage	567.7V	565.69V	565V
4	RMS o/p current	1.73A	1.75A	1.77A
5	Active Power	942.816W	881.06W	870W
6	Apparent Power	982.1VA	989.96VA	1000VA
7	Power factor	0.89	0.89	0.87
8	Efficiency	92%	94%	94%

Table 5.14 Comparison of different implemented closed loop control techniques in the form of different parameters with motor load

Sr. No.	Parameter	Closed loop PID	Closed loop ANN	Closed loop Fuzzy logic controller
1	THD in voltage	2.76%	2.84%	2.90%
2	THD in current	1.69%	1.72%	1.72%
3	RMS o/p voltage	176.75V	176.77V	169.73V
4	RMS o/p current	36.92A	36.94A	36.52A
5	Active Power	6264.58W	6334W	6012W
6	Apparent Power	6525.61VA	6529.88VA	6198.5VA
7	Power factor	0.96	0.97	0.97
8	Efficiency	90%	92%	92%

5.3 Contribution-3: Hardware implementation, results and discussion

To compare and improve the performance of parameters like efficiency, total harmonic distortion, power factor with the help of hardware implementation of available controlling techniques and proposed technique of ANN based closed loop PWM technique.

Implementation of nine level Multilevel converter is done with the help of components mentioned below

1. Raspberry pi hardware.
2. TLP 250 Mosfet drivers
3. MOSFET IRFZ24N
4. Resistance
5. Inductor
6. Capacitor
7. AC voltage sensor ZMPT101B

Specification for hardware implementation is given in the table 5.15

Table 5.15 Specifications for hardware Implementation.

Sr. No.	Parameters	Values
1	No. of Converters	4
2	No. Of Levels	9
3	DC input Voltage	6 V
4	Load Resistance	200 Ω
5	Load Inductance	100 mH
6	Filter Capacitor	100 μF
7	Filter Inductor	100 mH
8	Switch used	IRFZ24N

The circuit of an ANN-based multilevel inverter is simulated and run using MATLAB. The Raspberry Pi is a subsystem added to the existing simulation model.xslx file. The purpose of using the pi subsystem is to

deliver the pulses to the GPIO pins of the Raspberry Pi. The switching pulses are generated by the Raspberry Pi. Sixteen switching pulses are generated for the sixteen MOSFETS used in the cascaded H-bridge multilevel inverter. The switching pulses generated are of low magnitude. To increase the magnitude to 5V for switching pulses to drive the MOSFETS, TLP 250 drivers are used. Here we use voltage feedback. The output voltage is feedback and compared with the reference signal. A corresponding error signal is generated to change the switching angles to adjust the peak output voltage of 24 V.

Each cascaded H-bridge inverter uses 6 V as an input. As we use four cascaded H-bridge inverters to obtain 24 V peak voltage, we require four 6V power supplies. A filter inductor of 100mH and a filter capacitor of 50 microfarad are used to reduce ripples. Fig. 23 shows the output voltage waveform obtained, and Fig. 5.52 shows the hardware setup. The comparison of results is tabulated in table 5.15 and 5.16

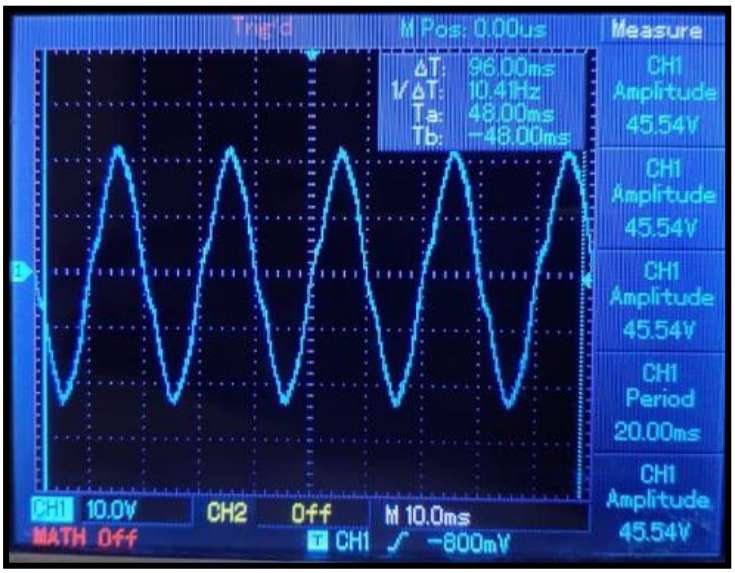


Fig. 5.59 Output voltage waveform from ANN based closed loop method

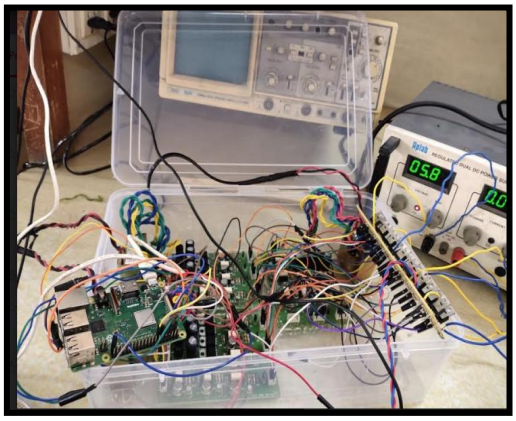


Fig. 5.60 hardware set-up of ANN based closed loop multilevel converter

Table 5.16 Comparison of parameters obtained with Hardware implementation using open loop methods

Sr. No.	Method	Output peak voltage	RMS load voltage	RMS load current	THD in current	THD in voltage	Efficiency
1	Open Loop control	22 V	15 V	75 mA	18.48 %	18.20 %	80%
3	Open loop PWM controlled	23.5 V	15.3 V	76 .5 mA	6.5%	6.32%	88%

Table 5.16 Comparison of parameters obtained with Hardware implementation using closed loop methods

No.	Method	Output peak voltage	RMS load voltage	RMS load current	THD in current	THD in voltage	Efficiency
1	Closed loop Fuzzy logic controller	23 V	14.5 A	74 mA	8.34%	5.99%	88%
2	ANN based closed loop PWM	24 V	16 V	80 mA	7.3%	5.76%	90%

6 Conclusion

- Open loop control techniques with R and RL loads are simulated and implemented by hardware which gives highest of THD and lowest value of efficiency.
- Open loop PWM techniques gives rise to lower value of THD and high value of efficiency as compared to open loop technique.
- Closed loop techniques of PID, ANN and fuzzy logic controller are implemented by software simulation and hardware for R, RL and motor loads. Simulations are carried out for 200V peak and 800V peak. It is found that ANN gives best results for R, RL and motor loads.
- ANN gives lowest value of THD in current 2.53% for R load, 1.00% for RL and 1.72% for motor load.
- ANN gives best results in the form of THD for 5.76% in current and and efficiency of 90% for hardware implementation by simulation and provides highest efficiency as compared to other methods.

7 Future scope

Multilevel converters has very wide range of applications. In multilevel converters using PWM the switches used has to on and off continuously. Due to high speed of switching, more switching loss is encountered. Power devices with low switching losses can be used . Efficiency can be increased further by the use of another controller instead of pi.

8 Publications

[1] Mohan Selokar and Manoj Sankhe, "Implementation of an ANN-based closed-loop Multilevel Inverter," International Journal of Mechanical Engineering, Vol.6 No.3, pp.1707-1712.(Scopus indexed journal) (Dec 2021 publication)(cite score-5.2). ISSN: 0974-5823.

[2] Mohan Selokar and Manoj Sankhe, "Applications of adaptive learning algorithms for THD reduction in nine level closed loop Multilevel Inverters," Semiconductor Opto-electronics. (Scopus indexed journal)

[3] Mohan S. Selokar and Manoj Sankhe, "Harmonic minimization in a Multilevel Converter Using an Adaptive Learning Algorithm," International Journal of Engineering and Applied Physics, Vol. 1, No. 3, pp. 31-318.ISSN: 2737-8071.

[4] Mohan S. Selokar and Manoj Sankhe, "A Dynamical Control in Multilevel Converter Using an Adaptive Learning Algorithm," pages 1333-1338 in the 2020 International Conference on Smart Electronics and Communication(ICOSEC). Published in IEEE Explore.
https://doi.org/10.1109/ICOSEC49089.2020.9215230.

[5] Mohan S. Selokar, Manoj Sankhe, "Harmonic minimization in Multilevel converter using an adaptive learning Algorithm", International conference at A. C. Patil college of Engineering held in September-2021.

9 References

1 J. Rodriguez, J. S. Lai and F. Z. Peng, "Multilevel inverters: Survey of topologies, controls, and applications," IEEE Trans. Ind. Elect., vol. 49, no. 4, pp. 724-738, Aug. 2002.

2. Beser, E.; Camur, S.; Arifoglu, B.; Beser, E.K. , " De-sign and application of a novel structure and topology for multilevel inverter," in Proc. IEEE SPEEDAM, Tenerife, Spain, 2008, pp. 969 – 974.

3. R.H. Baker, "High-Voltage Converter Circuit," U.S. Patent Number 4,203,151, May 1980.

4. S. Mekhilef and M. N. Abdul Kadir "Voltage control of three-stage hybrid multilevel inverter using vector transformation" IEEE Trans. Power Electron.,vol.25,no.10,pp 2599-2606, Oct. 2010.

5. L.M. Tolbert, F. Z. Peng, T. G. Habetler, "Multilevel PWM Methods at Low Modulation Indices," IEEE Trans. Power Electron.,vol. 15, no. 4, pp. 719-725, July 2000.

6. M. N. A. Kadir S. Mekhilef, and H. W. Ping "Voltage vector control of a hybrid three-stage eighteen-level inverter by vector decomposition" IET Trans. Power Electron.,vol.3,no. 4, pp.601- 611, 2010.

7. E. Babaei, M. T. Haque, and S. H. Hosseini, "A novel structure for multilevel converters," in Proc. ICEMS, 2005, vol. 2, pp. 1278–1283.

8. A. Nabae, I. Takahashi, and H. Akagi, "A new neu- tral-point clamped PWM inverter," IEEE Trans. Ind. Applicat., vol. IA-17, no. 5, pp. 518– 523, Sep./Oct 1981 .

9. T. A. Meynard and H. Foch, "Multilevel conversion: High voltage choppers and voltage-source inverters," in Proc. IEEE PESC, Toledo , Spain 1992, pp. 397– 403.

10. S. Mekhilef and M. N. Abdul Kadir "Novel vector control method for three-stage hybrid cascaded multilevel inverter" IEEE Trans. Ind. Elect., vol. 58, no. 4, pp. 1339-1449, May 2010.

11. S. Mekhilef, A. M. Omar and N. A. Rahim, "Mod- eling of three-phase uniform symmetrical sampling digital PWM for power converter" IEEE Trans. Ind. Electron.,vol. 54, no. 1, pp.427-432, Feb. 2007.

12. Carlos Roncero-Clemente, Oleksandr Husev, V. Miñambres-Marcos, Enrique Romero-Cadaval, Serhii Stepenko, Dmitri Vinnikov, "Tracking of MPP for three-level neutral-point-clamped qZ-source off-grid inverter in solar applications". Informacije MIDEM. Journal of Microelectronics, Electron-ics Components and Materials. ISSN 0352-9045, Vol.43, No. 4, 2013, pp. 212-221. December 2013.

13. M. F. Aiello, P. W. Hammond, and M. Rastogi, "Modular Multilevel Adjustable Supply with Parallel Connected Active Inputs," U.S. Patent 6301 130,Oct. 2001.

14. L. M. Tolbert, F. Z. Peng,"Multilevel converters as a utility interface for renewable energy systems," in Proc. IEEE Power Eng. Soc. Summer Meeting 2000 ,vol. 2 , pp. 1271-1274.
15. L. M. Tolbert, F. Z. Peng, T. G. Habetler, "Multilevel Inverters for Electric Vehicle Applications," IEEE Workshop on Power Electronics in Transporta- tion, Dearborn, Michigan, 1998, , pp. 1424-1431.
16. M. N. Abdul Kadir S. Mekhilef and H. W. Ping,"Dual vector control strategy for a three –stage hybrid cascaded multilevel inverter," Journal of power Electronic, vol.10, no.2,pp.155-164,2010.
17. P. Karuppanan and Kamalakanta mahapatra, '' PI ,PID and Fuzzy logic controlled cascaded volt- age source inverter based active filter for phone line conditioners," Wseas transactions on power systems,vol.6 ,no.4 ,pp 100-109, Oct 2011.
18. Towleong Tiang and Dahamen Ishak, ''Modelling and simulation of dead beat based PI controller in a single phase H-bridge inverter for stan- dalone applications," Turkish journal of electrical engineering and computer sciences , 22, pp 43- 56,2014.
19. Ngbin.: A Novel DC-Power Control Method for cascaded H-Bridge Multilevel Inverter. IEEE Trans. On industrial Electronics 2017 .
20. Jeyabharath Rajaiah.," Harmonic Minimization in seven level cascaded multilevel Inverter using Evolutionary Algorithm.," Circuits and Systems , 2016, pp2309-2322.
21. Li C. H. Ynag et al.," A self Learning Particle swarm optimizer for global Optimization.," IEEE Transactions on Systems, Man and Cybernetics(2012).
22. Rodriguez, J., Lai, J.-S. and Peng, F.Z. (2002,).,"Multilevel Inverters: A Survey of Topologies,
23. Controls,and Applications.," IEEE Transactions on Industrial Electronics, 49, 724-738
24. Taghizadeh, H. and Tarafdar Hagh, M. (2010).," Harmonic Elimination of Cascade Multilevel Inverters with Non Equal DC Sources Using Particle Swarm Optimization", IEEE Transactions on Industrial Electronics, 57, 3678- 3684.
25. Roh Chan.," Simple Algorithm with fast dynamics for cascaded H-bridge Multilevel Inverter based on Model Predictive Control Method," IEEE Conference Proceedings(2017)
26. F. J. t. Filho," Real time Selective Harmonic Minimization in cascaded Multilevel Inverters with varying DC sources," IEEE Power Electronics specialists Conference (2008).

27. Ricardo P. Aguilera et al, " Model Predictive Control of Cascaded H-Bridge Inverters based on a Fast-Optimization Algorithm," IEEE Conference(2015).

28. Daliang Yang et al, "Natural Frame Control of Single-Phase Cascaded H-Bridge Multilevel Converter Based on Fictive-Phases Construction," IEEE transactions on Industrial Electronics(2018)

29. Mohan Selokar, Manoj sankhe, " Harmonic in multilevel converter using an adaptive learning algorithm," International journal of engineering and applied physics, vol 1 No-3,pp. 311-318

30. Libing Wang et al, " A Real-Time and Closed-Loop Control Algorithm for Cascaded Multilevel Inverter Based on Artificial Neural Network.", Hindawi Publishing Corporation The Scientific World Journal Volume 2014, Article ID 508163

31. Tarmizi Tarmizi, " Design and verification of improved cascaded multilevel inverter topology with asymmetric DC sources," Journal of Power Electronics, Vol 19, No 5 pp 1074-1086, septemeber 2019